Rept. Invest. 41
Smokeless Briquets
Smoke Index
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STATE OF ILLINOIS
HENRY HORNER, *Governor*
DEPARTMENT OF REGISTRATION AND EDUCATION

DIVISION OF THE
STATE GEOLOGICAL SURVEY
M. M. LEIGHTON, *Chief*

REPORT OF INVESTIGATIONS—NO. 41

I. SMOKELESS BRIQUETS: IMPACTED WITHOUT BINDER FROM PARTIALLY VOLATILIZED ILLINOIS COALS

Progress Report of a Laboratory Investigation

II. SMOKE INDEX: A QUANTITATIVE MEASUREMENT OF SMOKE

BY

R. J. PIERSOL

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PREFACE

In 1931 in planning a research program to improve the utilization of Illinois coal, one problem which presented itself was the processing of slack coal into a product which would extend its marketability and value. Success in such a project would be of importance to the State, since it would provide a better domestic fuel from its own resources, and would promote the development of the coal industry of the State, since approximately one-half of the sized coal produced in Illinois is slack coal (less than 2 inches) which offers problems of marketing for many mines, particularly during certain seasons of the year.

The experimental investigation was begun along the line of briquetting slack coal without a binder. A binder, such as tar, is not only expensive, costing approximately 70 cents per ton of briquets, but it also adds to the smokiness of the resultant fuel.

Preliminary attempts were made to briquet Illinois coals without binder by heating and applying steady pressure, but this method did not show promise of commercial success, as noted in the first part of Report of Investigations No. 31. However a systematic investigation of the combined effect of heating and impact blow, rather than steady pressure, yielded excellent briquets, without binder. This was reported in the second part of Report of Investigations No. 31 and in Report of Investigations No. 37.

Still later it was discovered that this same process could be used in making smokeless briquets without binder, by first removing the smoke producing constituents from the coal. If common binder were used the resultant briquet would not be smokeless.

The term smokeless, as used in this report, is used in the trade sense. The trade designates certain low volatile bituminous coals, like those occurring in certain beds in West Virginia and adjacent states, as smokeless. They are not truly smokeless, but by the ordinary processes of combustion they yield relatively little smoke as compared with high volatile bituminous coals. In view of this common usage of the term smokeless, the same term is used for products made from high volatile bituminous coals which yield the same amount of smoke as, or less smoke than, the so-called smokeless coals.

In the progress of the work it became desirable to develop a laboratory method for a quantitative measurement of the amount of smoke liberated in combustion in order to permit comparison of the smokiness of impact briquets made from coal with partial volatilization with that of the corresponding raw coals. This method is herein referred to as the *smoke index* method. The smoke index method made it possible later to determine the degree of volatilization of the coal necessary to make smokeless briquets.

Part I of this preliminary report deals with smokeless briquets made by impact without binder from partially volatilized Illinois coals.

Part II deals with the smoke index method and its application to the measurement of smoke in naturally occurring and in processed coals.

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CHAPTER I—SUMMARY

SMOKELESS BRIQUETS may be made from prepared Illinois smokeless coal fines from which 15 per cent of the volatile matter (dry basis) has been driven off, with the same briquetting equipment and the same magnitude of impact as briquets made from raw coal, using no artificial binder. The briquetting temperature of the prepared smokeless fines, however, must be between 300° and 400°C. as contrasted to a temperature of 250°C. for the natural coal fines.

The mechanical strength of smokeless briquets, as determined by tumbling tests, is slightly greater than that of briquets made from raw coal by the impact method, using optimum conditions for both.

Actual power consumption during commercial production can be determined only by commercial scale production. However, the impact energy necessary to make one ton of briquets could be supplied by 50 pounds of coal, if the coal is so burned as to produce one horsepower-hour for each two pounds of coal. In order to drive off the desired 15 per cent volatile matter (dry basis), the coal must be preheated up to a temperature of about 900°F. (483°C.). Thus, with the above combustion efficiency, it may be calculated that in general about 150 pounds of coal are required for preheating one ton of smokeless briquets. These calculations are dealt with more fully on pp. 29-30.

CHAPTER II—INTRODUCTION

NEED FOR SMOKELESS FUEL

There is a special need for a cheap smokeless domestic fuel, particularly in the Middle West. While modern stoker equipment has been rather widely employed in industry, with the result that the destructive and harmful effects of smoke from industrial plants have been considerably reduced, yet in the domestic field much less has been accomplished. Estimates based upon a recent survey[1] made in Chicago are that the smoke produced by the domestic group in Chicago since 1911 has increased ninefold for 302,000 homes and four-flat apartments, and sixteenfold for 16,000 six-flat or larger apartments. At present, according to this report, 63 per cent of the smoke in Chicago is produced by the domestic furnace, notwithstanding the fact that it consumes only 49 per cent of the coal.

It is a difficult matter to compel domestic consumers to install better equipment. Possible solution lies in two lines of effort: (1) education to improve firing methods and to install mechanical equipment wherever it can be afforded; and (2) placing upon the market a prepared coal which will burn without smoke at a cost that will attract the domestic consumer to its use.

There is no one universal choice of a smokeless fuel within the price range of the majority of domestic users. Coke is favored by some and it appears that its use is gaining headway. Up to the present, however, Illinois coals have not been extensively coked, but indications are that they will be increasingly made into coke. In view of the vast resources of coal in Illinois and the importance of knowing their coking possibilities, the State Geological Survey is carrying on investigations of their coke, gas, and by-product making properties, and plans to publish a report at an early date.

The present report, however, concerns the preliminary results of another line of study, namely the preparation of smokeless briquets made by impact without binder from partially volatilized Illinois coals. The discoveries made appear to be promising for providing the domestic consumer with another type of smokeless fuel at a cost that will allow it to enter the competitive market with other fuels.

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[1] Blackwell, H. D., Chicago smoke survey shows need of education, better equipment: Coa Heat 27, March, p. 5 (1935).

COMPARISON OF PRESENT AND FORMERLY DESCRIBED BRIQUETS

The partially volatilized coal product used for making impacted smokeless briquets differs in composition, properties, and appearance from that of previously described products made from Illinois coals.[2] The present product retains a high volatile content (from about 25 to 30 per cent) as contrasted to other smokeless products of relatively low volatile content (usually less than 15 per cent); it retains its granular form as contrasted to other smokeless products possessing a cellular coke-like texture; and it has a high specific gravity, sinking in water, as contrasted to other semi-coked products which have a specific gravity from 0.5 to 0.7. The specific gravity of the smokeless briquet is over 1.2. Because of their relatively greater density, smokeless briquets burn with less rapidity than porous coke.

PROTECTION OF PROCESS BY PATENT

The process of making smokeless briquets without binder has been protected in the interest of the people of Illinois by U. S. Patent No. 2,021,020. Also, it is planned to apply for patent to protect the discovery that a non-coke smokeless fuel, retaining a relatively high volatile matter content, may be processed from Illinois coals by the preferential distillation of the low-temperature fractions of the volatile matter.

ACKNOWLEDGMENTS

Samples of Illinois coal for processing and for smoke index tests were furnished through the courtesy of various Illinois coal mining companies.

The impact machine of the Department of Theoretical and Applied Mechanics of the University of Illinois was used through the courtesy of Professor M. L. Enger, Dean of the College of Engineering.

J. M. Nash and H. C. Roberts, assistants in the Physics Division, and for a brief time, Dr. F. W. Cooke, carried on the laboratory tests and assisted in construction of apparatus. Chemical analyses were made in the analytical laboratory of the Survey under the direction of Dr. O. W. Rees, Associate Chemist. Assistance in preparation of the report was furnished by Dr. G. H. Cady, Head of the Coal Division of the Geological Resource Section, and by Dr. M. M. Leighton, Chief.

[2] The reader is referred to the following publications by S. W. Parr: Anthracizing of bituminous coal, Illinois State Geol. Survey Bull. No. 4, p. 196, 1906; The modification of Illinois coal by low temperature distillation, Univ. of Illinois Eng. Exp. Sta. Bull. No. 24, 1908; The coking of coal at low temperatures, Univ. of Illinois Eng. Exp. Sta. Bull. No. 60, 1912; The coking of coal at low temperatures with special reference to the properties and composition of the product, Univ. of Illinois Eng. Exp. Sta. Bull. No. 79, 1915; and Low temperature carbonization of coal, Second International Conference on Bituminous Coal, p. 54, Vol. I, 1928.

CHAPTER III—SMOKELESS BRIQUETS

INTRODUCTION

The use of fine sizes of coal in the production of a briquet by impact and without use of an artificial binder has been shown to be possible.[1] By a partial volatilization of the coal before impacting, smokeless briquets can be made by the same general technique.

DESIRABILITY OF SMOKELESS COAL BRIQUETS

Smokeless coal, prepared by partial volatilization, would be in an unmarketable form for many uses unless subsequently briquetted. The smokeless impact briquets possess several advantages over many other solid fuels. They are preferable to briquets made from carbonized coal with the aid of a binder because such briquets are usually smoky. Their ignition and maintenance temperatures are believed to be lower than those of most natural smokeless coals because of their remaining higher volatile matter content.

In the tests made in an open grate they burned without swelling and disintegration, presumably on account of the prior removal of low-temperature volatile fractions. Due to their dense structure, they burned from their surface inwardly, similar to a hard coal rather than a soft coal.

They are clean to handle as compared with raw bituminous coal and possess the same advantages as any other briquetted coal in respect to uniformity of size and structure.

METHODS OF PRODUCTION OF SMOKELESS BRIQUETS

There are at least four methods by which essentially smokeless briquets may be made, namely: (1) subsequent carbonization of coal briquets, formed with binder; (2) subsequent carbonization of coal briquets formed without binder; (3) briquetting of carbonized coal using a binder (which adds to the smokiness of the resultant briquet to an extent depending upon the smokiness of the binder); and (4) the process herein described which consists of briquetting without binder, by impact, processed smokeless coal fines.

In regard to (1), several processes have been devised for subsequent carbonization of coal briquets containing binder, but none of these has assumed commercial importance in the United States.

[1] Piersol, R. J., Briquetting Illinois coals without a binder by impact. Second Report: Illinois State Geol. Survey Report of Investigations No. 37, 1935.

In regard to (2), a summary of the various methods of producing briquets without binder for subsequent carbonization was presented in a previous report.[2]

At an early stage in the present investigation, an attempt was made to partially carbonize briquets made from natural coal by impact without binder. Preliminary results showed that ordinary briquets could be transformed into smokeless briquets with but slight swelling and cracking, but involving a considerable loss in mechanical strength.

In the meantime, it was discovered that coal prevolatilized to a smokeless degree could be impacted without binder directly into a smokeless briquet possessing a mechanical strength greater than that of a briquet made direct from the same natural coal by impact without binder. Therefore, the former line of attack was dropped in favor of this method.

In regard to (3), various carbonized fuels, such as coke breeze, petroleum coke, and charcoal, and also anthracite fines are briquetted with binder. An excellent summary of the literature on briquetting carbonized fuel with binder is given by Stillman,[3] and a review of the more recent literature is given by the author in the two reports previously cited.

BRIQUETTING WITHOUT BINDER, BY IMPACT, OF PROCESSED SMOKELESS COAL FINES

The fourth general method of producing smokeless briquets is the process herein described, which consists of briquetting by impact, without binder, processed bituminous coal fines from which the smoke-producing content has been removed. So far as is known, there is no previous literature on this line of investigation.

COALS USED IN THE INVESTIGATION

For determining the relationship between the volatile matter of raw coals and their smokiness a series of six banded bituminous coals were used of rank varying from high volatile bituminous *C* to low volatile coal. The high volatile bituminous *C* rank was represented by coal from Will County, Illinois, with a rank index of 120[4] and by coal from Washington County with a rank index of 126[5]; the high volatile bituminous *B* rank was represented by coal from Franklin County with a rank index of 131[6]; medium volatile

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[2] Piersol, R. J., Briquetting Illinois coals without a binder by compression and by impact: Illinois State Geol. Survey Report of Investigations No. 31, 1933, pp. 14-15.

[3] Stillman, A. L., Briquetting applied to carbonized coal, "Briquetting" pp. 336-357, The Chemical Publishing Company (1923).

[4] State Geol. Survey Bulletin 62, p. 222, Mine Index No. 359.

[5] Idem. p. 279. Mine Index 86.

[6] Idem. p. 314, average for Franklin County.

bituminous coal was represented by coal from the Jewell bed, Wyoming County, West Virginia, with dry mineral-free volatile matter content of 23.3 per cent; and low volatile bituminous coal by two coals from the Beckley bed, one from Beckley County and the other from Raleigh County, West Virginia, with dry mineral-matter-free and volatile matter content of 18.1 and 16.4 per cent respectively. Coals of intermediate rank—high volatile bituminous *A* were not used in the investigation. These coals were also used as a basis of comparison of the smokiness of partially devolatilized coals in the form of briquets and of natural smokeless coal.

Table 1 shows the proximate analyses of the Illinois coals used for making smokeless briquets and of the Illinois and West Virginia coals used for smoke index tests of natural coals. Analyses herein reported for the Illinois coals were made in the Analytical Laboratory of the Geological Survey and those for the West Virginia coals were obtained from Black's Directory, Fourth Edition, 1935.

The detailed results of the effect of the degree of volatilization on the smoke index and the influence of the percentage of naturally occurring volatile matter on the smoke index of the coal are given in Part II.

EQUIPMENT USED IN THE PARTIAL VOLATILIZATION OF ILLINOIS COALS

The laboratory equipment for processing coal by removal of low-temperature volatile fractions consists of a rotary oven in which the coal is partially volatilized and an exhaust hood for removing the escaping gases. The equipment for the quantitative measurement of the smoke content of both natural and processed coals consists of a smoke index apparatus, to be described.

Rotary oven.—The rotary oven used for the partial volatilization of coal in this investigation is a modification of that[7] used previously for the preheating of coal to be briquetted.

The present rotary oven consists of a heating cell, constructed from a 5¾-inch length of 3⅛-inch pipe, so mounted as to rotate within a stationary 6-inch length of 3½-inch pipe, around which is wound the heating element. For the insertion of a thermocouple, a ¼-inch copper tube, with its inner end closed, extends to the center of the cell through the rear end which is removable by means of a spanner wrench. The front end of the cell is closed by a permanent steel inset, through which there extends outwardly a 3-inch length of ¼-inch steel tubing that serves both as an outlet for the escaping gas and as a means for rotating the heating cell. The rear end of the stationary pipe is closed by a transite inset with an opening through which the thermocouple passes; the front end is open.

[7] Piersol, R. J., Briquetting Illinois coals without a binder by impact. Second Report: Illinois State Geol. Survey Report of Investigations No. 37, Fig. 1, p. 21, 1935.

TABLE 1.—PROXIMATE ANALYSES OF COALS USED FOR SMOKE INDEX AND BRIQUETTING TESTS

Analysis No.	Date of analysis	Location	Bed	Condition (*a*)	Moisture	Ash	Volatile matter	Fixed carbon	Total sulfur	B. t. u.
Samples used for smoke index of volatilized coals										
C-738	1934	Will Co.	2	2	....	5.3	43.9	50.8	3.4	13299
C-740	1934	Franklin Co.	6	2	....	7.1	35.9	57.0	1.1	13246
Samples used for smoke index of natural coals										
C-418	1933	Will Co. (B) (*c*)	2	1	9.1	4.7	43.5	42.7	2.9	12369
				2	....	5.2	47.8	47.0	3.2	13605
				3	....	....	....	....	....	14517
(*d*)	1934	Washington Co. (*c*)	6	1	8.5	7.2	41.5	42.8	4.2	11913
				2	....	7.8	45.4	46.8	4.6	13030
				3	....	....	....	....	....	14448
(*e*)	1934	Franklin Co. (B)	6	1	8.7	10.0	33.8	47.5	2.0	11640
				2	....	10.9	37.0	52.1	2.1	12746
				3	....	....	....	....	....	14513
(*f*)	1934	Raleigh Co., W. Virginia (A)	Beckley	1	0.7	5.2	16.2	77.9	0.7	15120
				2	....	5.2	16.3	78.5	0.7	15227
				3	....	....	....	....	....	17160
(*g*)	1921	Beckley Co., W. Virginia (B)	Beckley	1	....	....	....	....	....	....
				2	....	5.0	17.7	77.3	0.6	14850
				3	....	....	....	....	....	15720
(*h*)	1935	Wyoming Co., W. Virginia (C)	Jewell	1	1.4	4.0	22.5	72.1	0.6	14750
				2	....	4.1	22.8	73.1	0.6	14957
				3	....	....	....	....	....	15670

(*a*) 1—as received basis; 2—moisture-free basis; 3—unit coal basis (dry mineral matter free)
(*b*) Heated to 250°C. before analysis. Reported on dry basis. Moisture less than one per cent on as received basis.
(*c*) Partly air dried.
(*d*) Calculated from mine average moisture- and ash-free values, Bull. 62, p. 186, Mine No. 86, average of three samples given.
(*e*) Calculated from mine average moisture- and ash-free values, Bull. 62, pp. 140-141, Mine No. 136, average of nine samples given.
(*f*) Bed average obtained from Mine No. 189, p. 289, Black's Directory, Fourth Edition, 1935.
(*g*) Bed average obtained from Mine No. 99, p. 283, Black's Directory, Fourth Edition, 1935.
(*h*) Bed average obtained from Mine No. 19, p. 277, Black's Directory, Fourth Edition, 1935.

Exhaust system.—The exhaust system consists of a 10 × 12-inch hood, supported over the front end of the rotary oven, and connected through a flexible tubing to a vacuum cleaner unit that discharges outside of the building through 2-inch piping.

EQUIPMENT USED FOR BRIQUETTING

The laboratory equipment used in making smokeless briquets consists of a Turner impact machine and a briquetting die. A tumbling barrel is used to determine the mechanical strength of the briquets.

Impact apparatus.—The Turner impact machine[8] consists of two vertical standards serving as guides for drop hammers of various weights, from 50 to 500 pounds, which are raised to the desired height by an electromagnet and dropped by breaking the electric circuit.

Briquetting die.—The impact dies used in making smokeless briquets are all of the same design as the compaction die used previously.[9] The spool-shaped die is made of cold rolled steel, No. 2320 S. A. E., 3.5 per cent nickel, the wearing parts of which are case-hardened. The outer sleeve of the spool is wound with a heating coil, 20 feet of No. 19 resistance wire, which is covered with an asbestos jacket. Rheostat control permits maintenance of the temperature of the die at any desired value up to 400°C. At the higher temperatures hardened clarite steel, quenched at 600°C., is used for die parts. The temperature of the die is measured by a thermocouple inserted into an opening in the lower part of the outer sleeve. The cylindrical briquet, 1½-inch diameter, is impacted within the space confined by an inner sleeve, a fixed bottom plunger, and a movable top plunger. The impact blow from the hammer is transmitted to this movable plunger through an auxiliary plunger extending above the top of the die.

EQUIPMENT USED IN DETERMINING MECHANICAL STRENGTH

Tumbling barrel.—The same tumbling barrel is used as previously described in Report of Investigations No. 31. It consists of an 8-inch length of an 8-inch inside diameter pipe with ¼-inch wall, the ends of which are closed by round steel plates, ¼-inch thick, one being removable for the insertion and removal of briquets. Three equally spaced 1-inch angle irons that run the length of the barrel act as baffles. The barrel is half filled with flint pebbles, with a total weight of 5000 grams and an approximate weight of 25 grams each.

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[8] Illustrated in Fig. 8, p. 31, Report of Investigations No. 31.
[9] Illustrated in Fig. 2, p. 18, Report of Investigations No. 31.

SMOKE INDEX APPARATUS

The smoke index equipment[10] used in this investigation consists of, (a) an electric muffle furnace, so equipped that a specified temperature and rate of air supply can be maintained; (b) a light-absorption tube through which all smoke is drawn; and (c) a smoke density system composed of a source of a beam of constant intensity which passes through the absorption tube, a photo-electric cell at the other end of the tube, and a galvanometer.

EXPERIMENTAL PROCEDURE IN MAKING SMOKELESS BRIQUETS

Preparation of coal samples for partial volatilization.—Since the size of material which gave most uniform volatilization results and was best adapted to briquetting was minus 4-mesh, all samples were reduced to this size upon receipt at the laboratory, being stored in air-tight receptacles to avoid excessive moisture loss. Immediately before use, in either volatilization or briquetting tests, the samples needed were obtained by quartering from the storage sample.

In order to obtain approximately the same size briquets, either 45-gram or 50-gram samples were used, depending on the moisture content of the coal.

Removal of low-temperature volatile matter.—In making volatilization tests the steps in the procedure were as follows: (1) the temperature of the rotary oven (measured by the thermocouple inserted in the copper tube) was raised to a predetermined value by use of an appropriate equilibrium heating current, which maintained a constant temperature throughout the test; (2) the heating cell was removed from the stationary pipe, its removable end opened, the weighed quantity of coal inserted, the end closed, and the loaded cell replaced, the entire operation requiring about 30 seconds; (3) the exhaust motor was started; (4) throughout the test, the heating cell was hand-rotated rapidly at 1-minute intervals to prevent sticking of the coal and to insure uniform distribution of temperature and degree of volatilization; (5) at the end of the predetermined period of volatilization, the temperature of the coal was recorded; (6) the heating cell was removed; (7) the coal was cooled to a pre-determined temperature; and then (8) the coal was transferred from the heating cell to the impact die, previously heated to the same pre-determined temperature.

Briquetting technique.—In the formation of smokeless briquets, the partially volatilized coal at various specified temperatures was transferred to the impact die previously heated to various selected temperatures. The top surface of the coal in the die was leveled, and the movable plunger was lightly pressed down so that it entered the cylinder for a short distance. The loaded

[10] Piersol, R. J., Smoke index: a quantitative measurement of smoke. This report, pp. 49-51.

die was clamped to the foundation directly beneath the impact hammer as described in the preliminary report already cited. The auxiliary plunger supporting a 1-inch steel plate 4 $\times$ 4 inches, was inserted on top of the movable plunger. The 500-pound hammer was dropped from various selected heights, care being taken to avoid a second impact on the rebound. The die was unclamped, opened, and the briquet was pressed out of the inner cylinder by means of a hydraulic press at pressures between 500 and 1000 pounds. With downward taper (approximately 0.020-inch increase of diameter per inch) of the inside wall of the portion of the die surrounding the finished briquet, only a slight pressure is necessary to cause the briquet to fall out of the die. Each briquet was weighed immediately in order to determine its combined moisture and volatile loss.

PROCEDURE IN MAKING TUMBLING TESTS

The tumbling barrel was rotated at 40 r.p.m. for 2 minutes in the determination of the tumbling loss for smokeless briquets, all conditions being identical to those previously reported for the determination of the tumbling loss of ordinary briquets. Also, the weight and size of a smokeless briquet made from a 50-gram sample of coal is approximately the same as that of an ordinary briquet made from a 45-gram sample of coal. Therefore, the tumbling losses of the two kinds of briquets are directly comparable.

PROCEDURE IN DETERMINING SMOKE INDICES

Preparation of samples.—In preparing samples for smoke index determination seven or eight 1-cm. cubes were cut from each briquet and three or four cubes from the center of a lump of each coal tested. The latter were cut immediately before testing to avoid air-drying loss as much as possible. They were all approximately the same weight, as determined by actual weighing.

Smoke index method.—A complete statement of the smoke index method is given in Part II. Briefly, the procedure for the determination was as follows: The cube of coal, on a nickel dish set on a movable tray, was placed in the center of the furnace. The furnace was maintained at a temperature of 600°C. and with an air supply of 4 cubic feet per minute. Galvanometer readings were taken at 5-second intervals, starting at the instant the sample was placed in the furnace and continuing throughout the period of smoke liberation.

The total smoke was calculated as the product of the average amount of smoke produced and the time required for its liberation. The smoke index (smoke per gram) was obtained by dividing this total smoke content by the initial weight of the sample.

EXPERIMENTAL RESULTS

TUMBLING TESTS

The results concern (1) the effect of the amount of volatile matter removed on the mechanical strength of the resultant briquets, and (2) the effect of the briquetting temperature on the mechanical strength of the briquets.

Effect of amount of volatile matter removed on mechanical strength of briquets.—The influence of degree of volatilization on the mechanical strength of briquets was ascertained for Will County and Franklin County coals.

Will County coal was volatilized at temperatures of 373°, 448°, 460°, 466°, 475°, 485°, 494°, and 505°C. for ten minutes, then cooled to 300°C. and impacted by a 4½-foot drop of the 500-pound hammer.

It is shown in Table 2 (Fig. 1) that the volatile matter in briquets made from volatilized Will County coal may be as low as 31.9 per cent without

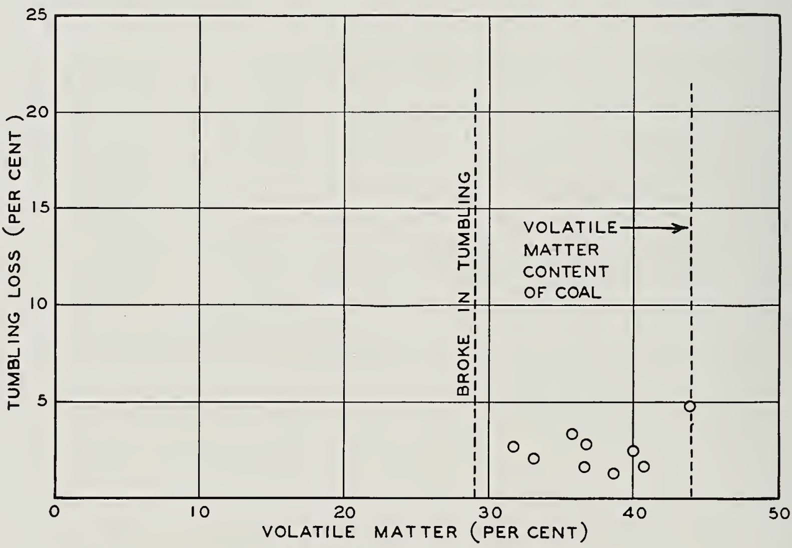

Fig. 1.—Mechanical Strength of Will County Briquets as Affected by Volatile Matter Content.

detrimentally affecting their strength. Such a briquet has a smoke index value less than one-third of that of West Virginia coals, as is shown on pages 28 and 106.

Franklin County coal was volatilized at temperatures of 425°, 440°, 455°, 470°, and 482°C. for ten minutes, then cooled to 300°C. and impacted by a 4½-foot drop of the 500-pound hammer.

TABLE 2.—MECHANICAL STRENGTH OF WILL COUNTY BRIQUETS AS AFFECTED BY VOLATILE MATTER

(DATA FOR FIG. 1)

Volatilization coal temperature °C.	Oven temperature °C.	Volatile matter (per cent)	Tumbling loss (*a*) (per cent)
373	425	43.7	4.8
448	490	40.5	1.8
460	500	39.8	2.7
466	510	38.5	1.3
475	520	36.8	2.9
475	525	36.4	1.8
485	530	35.7	3.4
494	540	33.0	2.2
505	550	31.9	2.8

(*a*) Percentage loss in weight after 2 minutes tumbling.

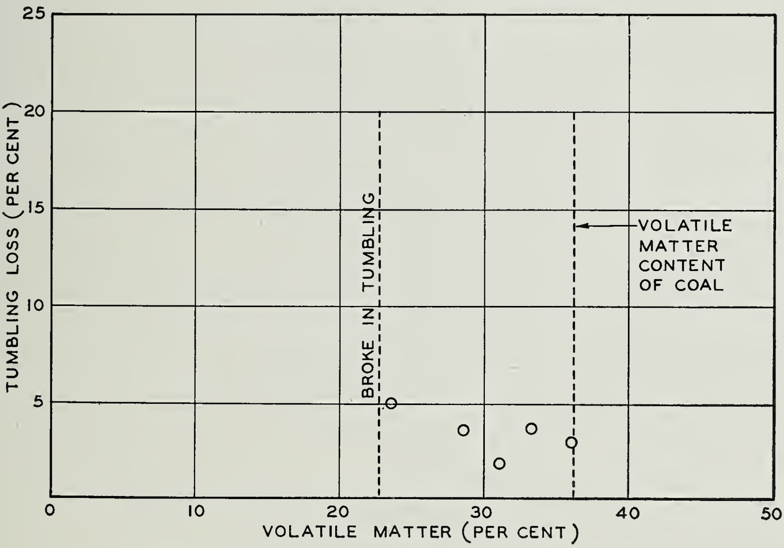

FIG. 2.—MECHANICAL STRENGTH OF FRANKLIN COUNTY BRIQUETS AS AFFECTED BY VOLATILE MATTER CONTENT.

The results of tumbling loss tests on a similar series of briquets made from Franklin County coal are shown in Table 3 (Fig. 2). The strength of these briquets is satisfactory for volatile matter content as low as 23.6 per cent. Such a briquet has a smoke index value less than one-seventh of that of West Virginia coals, as shown on pages 28 and 106.

Table 3.—Mechanical Strength of Franklin County Briquets as Affected by Volatile Matter

(Data for Fig. 2)

Volatilization coal temperature °C.	Oven temperature °C.	Volatile matter (per cent)	Tumbling loss (*a*) (per cent)
250	275	35.9	2.8
425	460	33.0	3.6
440	480	30.9	1.8
455	500	28.6	3.5
470	520	23.6	4.9
482	540	22.6	disintegrated

(*a*) Percentage loss in weight after 2 minutes tumbling.

Effect of briquetting temperature on mechanical strength of Will County smokeless briquets.—In this series of tests all conditions were maintained constant except the briquetting temperature (that of the impact die and that to which the coal was cooled). Briquets were made from Will County coal volatilized to 33.1 per cent volatile matter content at a temperature of 460°C. (coal temperature) maintained for five minutes, the shorter period and lower temperature being due to continuous rotation of the oven. Then the coal was cooled to the briquetting temperatures of 250°, 300°, 350°, and 400°C., and then impacted by a 4½-foot drop of the 500-pound hammer.

Table 4.—Mechanical Strength of Will County Smokeless Briquets Containing 33.1 per cent Volatile Matter, Impacted by a 4½-foot Drop of the 500-pound Hammer, from Coal Volatilized at 460 °C. (Coal Temperature) for 5 Minutes. as Affected by Briquetting Temperature

(Data for Fig. 3)

Briquetting temperature (°C.) (*a*)	Tumbling loss (*b*) (per cent)	
	Individual	Average
250	4.8	
250	5.1	5.0
300	1.9	
300	3.5	2.7
350	1.9	
350	1.1	1.5
400	1.3	
400	1.6	1.2
400	0.8	

(*a*) The briquetting temperature is that of the impact die and, also, that to which the coal is cooled subsequent to volatilization to 33.1 per cent volatile matter.
(*b*) Percentage loss in weight after 2 minutes tumbling.

Table 4 (Fig. 3) indicates that the mechanical strength of smokeless briquets increases with increasing briquetting temperature.

Although a briquetting temperature of 400°C. results in a slightly stronger briquet than that obtained at 300°C., nevertheless the latter temperature was selected for use in other tests since it did not require an impact die made of clarite steel.

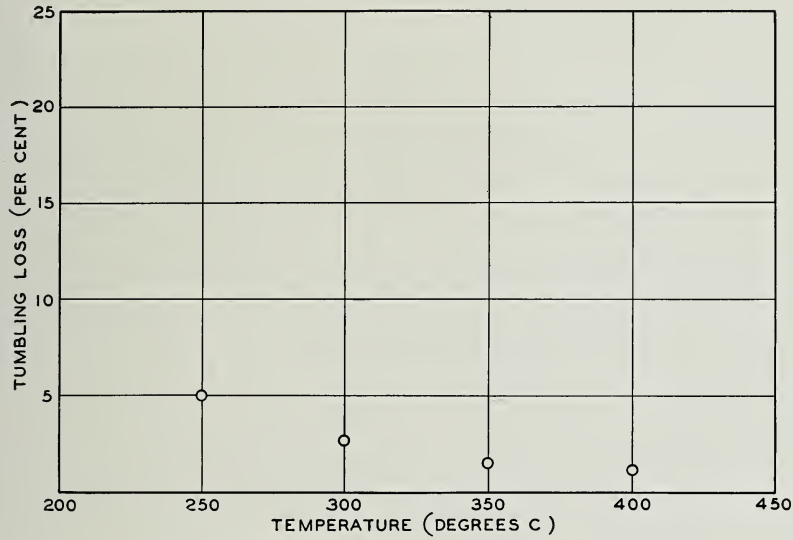

Fig. 3.—Effect of Briquetting Temperature on Mechanical Strength of Will County Smokeless Briquets.

No tests were made to determine whether the die should be held at the same temperature to which the coal has been cooled, because in the rapid commercial production of briquets the die would tend to maintain the same temperature as the coal.

TIME-TEMPERATURE CURVE FOR 15 PER CENT VOLATILE MATTER LOSS

There is a wide range of time (8.5 minutes to 40 minutes) possible for volatilization to produce the required reduction in volatile matter, the length of time decreasing with increased temperature of volatilization as shown in Table 5 (Fig. 4), but in commercial practice, in order to maintain the optimum volatile matter content, it would be essential to adjust the temperature to the period of volatilization, or vice versa. This is discussed more fully in Part II of this report, pages 107-110.

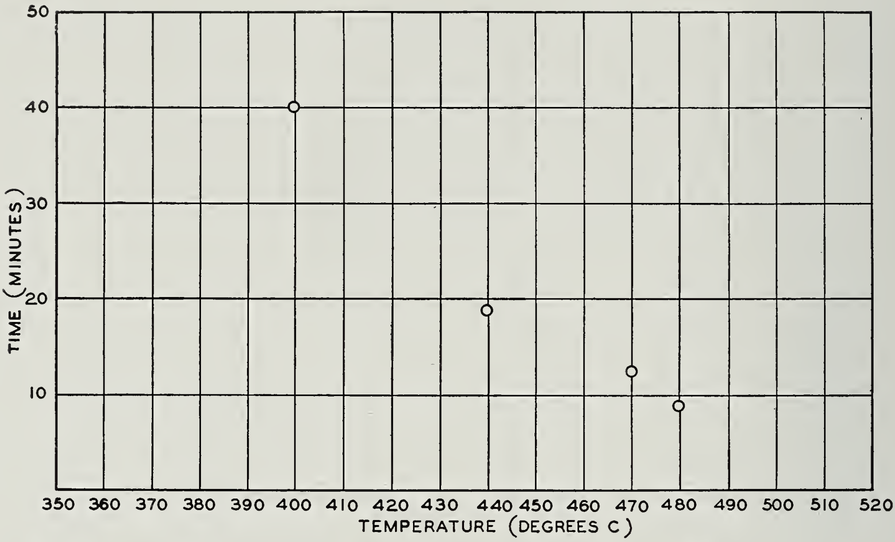

Fig. 4.—Time-Temperature Curve For 15 Per Cent Volatile Matter Loss For Will County Coal.

Table 5.—Time-Temperature Data for Optimum Volatile Matter Loss of Will County Coal

(Data for Fig. 4)

Volatilization period (minutes)	Volatilization temperature of the coal (°C.)	Oven temperature (°C.)	Weight loss (per cent)	Volatile matter (*a*) (per cent)
0	....	....	0.0	43.9
90	390	400	10.6	37.3
75	390	400	10.6	37.3
75	390	390	5.9	40.4
40	400	420	15.3 (*b*)	33.8
40	400	405	9.4	38.1
35	400	415	11.8	36.4
30	400	410	11.8	36.4
20	445	500	17.7	31.8
18.5	440	450	15.3 (*b*)	33.8
13	475	500	18.8	30.9
12	470	500	15.9 (*b*)	33.3
11	460	500	12.9	35.6
9	495	550	18.8	30.9
8.5	480	550	15.9 (*b*)	33.3

(*a*) Percentage volatile matter calculated from experimental weight loss, "dry basis."
(*b*) Optimum volatile matter loss is selected at a value of about 16 per cent (weight loss).

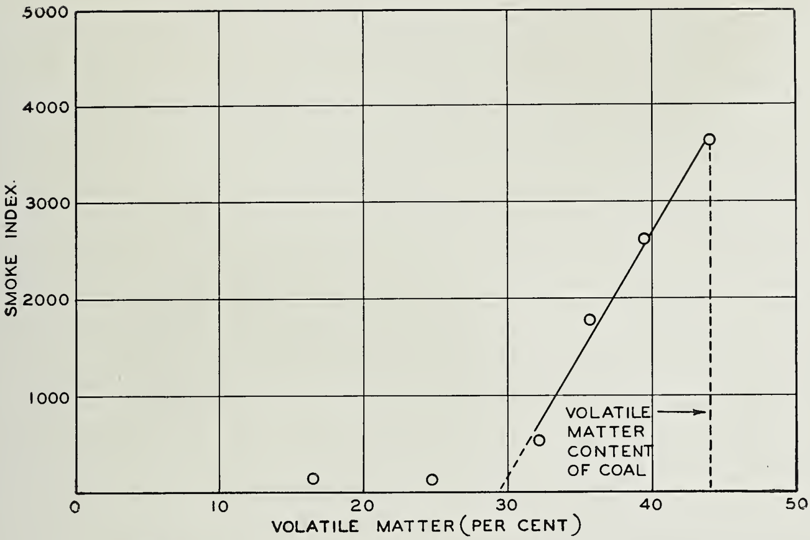

Fig. 5.—Effect of the Amount of Volatilization on the Smoke Index of Will County Briquets.

Table 6.—Summary of Data Showing the Effect of Amount of Volatilization on Smoke Index of Will County Briquets

(Data for Fig. 5)

Volatilization coal temperature (°C.)	250°	477°	485°	505°	515°	535°
Weight loss (per cent)...........	0.0	7.6	12.7	17.6	25.9	32.9
Volatile matter (a) (per cent).....	43.9	39.3	35.8	31.9	24.3	16.4
Test No.	*Smoke indices*					
1............................	3230	3540 (b)	1640	263	245	159
2............................	3670	1880	1590	777	98	96
3............................	4090	3360	1470	550	127	140
4............................	3800	3400	1880	273	64	188
5............................	3890	2030	1980	871	183	....
6............................	3460	3040	1820	526	66	....
7............................	3360	1730	1920	324	104	....
8............................	....	1910	1820	475	238	....
Average....................	3640	2610	1770	507	141	146

(a) Percentage volatile matter calculated from determined weight loss.
(b) Individual samples showed variation far beyond that to be expected from the heterogeneous structure of the coal, possibly due to greater volatilization of the smaller grains of coal.

SMOKE INDEX DETERMINATIONS

Table 6 (Fig. 5) is a summary table which shows the influence of the remaining percentage of volatile matter on the smoke index of briquets impacted from processed Will County coal. A 10-minute volatilization, at a coal temperature of 505°C., results in 17.6 per cent loss in volatile matter (also weight loss on a dry basis); thereby reducing the volatile matter content from 43.9 per cent to 31.9 per cent and reducing the smoke index from an average of about 3600 for the dry coal to an average of about 500 for the briquet impacted from the processed coal. This value of smoke index is less than one-third of that of a so-called West Virginia smokeless coal, the average smoke index value of such a coal, with a volatile content of 16.2 per cent, being 1770 (Table 25, West Virginia A coal, Part II of this report).

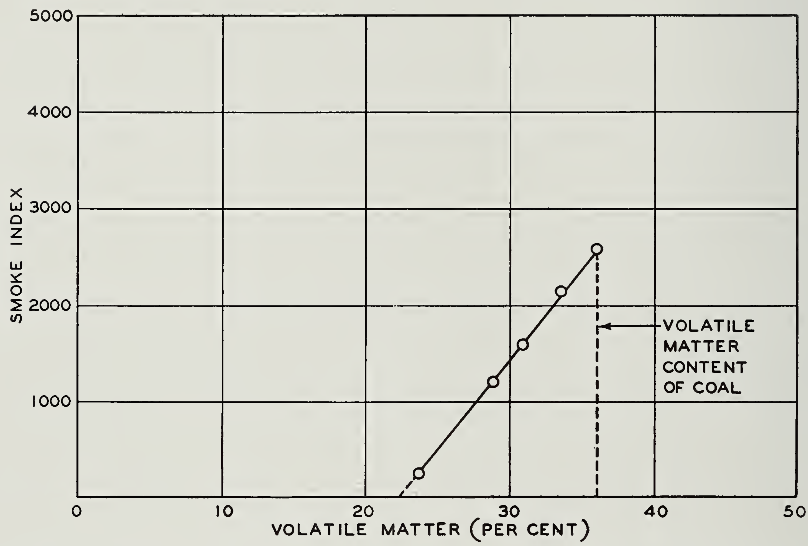

Fig. 6.—Effect of the Amount of Volatilization on the Smoke Index of Franklin County Briquets.

Table 7 (Fig. 6) is a similar summary table for the smoke index of briquets impacted from processed Franklin County coal. A 10-minute volatilization, at a coal temperature of 495°C., results in 16.1 per cent loss in volatile matter; thereby reducing the volatile matter content (dry basis) from 35.9 per cent to 23.6 per cent and reducing the smoke index from an average of about 2600 to an average of about 250, the latter value being less than one-seventh of that of the West Virginia smokeless coal. Reference may be made to Part II of this report for the detailed results on the smoke index of smokeless briquets.

TABLE 7.—EFFECT OF AMOUNT OF VOLATILIZATION ON SMOKE INDEX OF FRANKLIN COUNTY BRIQUETS

(DATA FOR FIG. 6)

Volatilization temperature (°C.)	250	450	465	480	495
Weight loss	0.0	4.3	7.3	10.3	16.1
Volatile matter (*a*)	35.9	33.1	30.9	28.5	23.6
Test No.	*Smoke indices*				
a	2480	2120	1140	956	175
b	2400	1940	1830	1580	86
c	2480	2490	1800	934	176
d	2670	2090	1910	1310	414
e	2710	2300	1650	937	47
f	2710	2580	1290	1610	449
g	2820	1620	1590	1220	170
h	2440	....	....	....	479
Average	2590	2160	1600	1220	250

(*a*) Percentage volatile matter calculated from experimental weight loss.

ESTIMATED ENERGY COSTS

Although actual power consumption can be determined only by commercial scale production, nevertheless, certain estimates may be made of the cost of the mechanical and heat energy required in making smokeless briquets.

Approximately the same impact energy is required as that for making ordinary impacted briquets. It was estimated in Report of Investigations No. 37 that 50 pounds of coal (so burned as to produce one horsepower-hour for each two pounds of coal) would be sufficient to supply the mechanical energy to make one ton of briquets.

On the above combustion efficiency, about 100 pounds of coal are necessary to preheat the coal for one ton of ordinary briquets, but for smokeless briquets approximately 50 per cent more heat is required, so that this method would require about 150 pounds of coal per ton of briquets.

An approximate calculation of the heat necessary to raise dry coal to a given temperature may be based on the specific heat of coal. In order to drive off the desired 15 per cent volatile matter the coal must be preheated up to a temperature of about 900°F. (482°C.). If the coal has an average temperature of 70°F. before preheating, this requires an increase of about 830°F. Since coal possesses a specific heat of approximately 0.3. it thus requires 249 B.t.u. to preheat one pound of dry coal. If coal is used as a source of fuel to volatilize the coal and if it is so burned as to deliver 5000

B.t.u. per pound of coal, then 100 pounds of coal is needed to preheat one ton of dry coal or 120 pounds of coal per ton of smokeless briquets. If the coal is not dry, an additional quantity of fuel is necessary to drive off the moisture, the quantity depending upon the percentage of moisture present. Thus in general about 150 pounds of coal are required for preheating one ton of smokeless briquets.

The total energy consumption is, therefore, equivalent to about 200 pounds of coal per ton of briquets.

The 15 per cent volatile matter liberated in processing coal to a smokeless product is readily combustible. Future tests will be made to determine the volume produced per ton of coal processed and its B.t.u. per cubic foot. If desired, this liberated gas may be burned to furnish a part, or perhaps all, of the fuel required to operate the briquetting unit.

The shrinkage of coal in producing a ton of smokeless briquets is equal to the percentage moisture plus 15 per cent, which is the amount of volatile matter removed. Therefore, for a particular Illinois coal containing 10 per cent moisture, the total shrinkage in making smokeless briquets would be 25 per cent of the coal used.

FUTURE INVESTIGATIONS

The present preliminary report describes an exploratory laboratory investigation in which it is shown beyond reasonable doubt that Illinois coal may be processed into a smokeless product by the removal of the very low-temperature fractions of its volatile matter and, second, that this product may be impacted without binder into strong smokeless briquets. This is being followed by further investigations which include:

(1) Operating range, including temperature and time of volatilization, impact die temperature, and impact pressure.

(2) Properties of smokeless briquets, including mechanical strength, smoke index, weathering and burning characteristics.

(3) Effect of the rank of coal and the coal components (banded ingredients), sulfur, and ash.

(4) Systematic tests on a variety of Illinois coals.

(5) Further detailed study of the processing of Illinois coal fines into a smokeless product for domestic consumption without subsequent briquetting.

II. SMOKE INDEX: A QUANTITATIVE MEASUREMENT OF SMOKE

R. J. PIERSOL

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SMOKE INDEX: A QUANTITATIVE MEASUREMENT OF SMOKE

CHAPTER I—INTRODUCTION

PURPOSE OF INVESTIGATION

IT HAS BEEN discovered that Illinois slack coal may be briquetted by impact without the use of an artificial binder,[1] and that excellent smokeless fuel briquets may be impacted without binder from Illinois slack coal which has been partially volatilized.[2] In the pursuit of the research on smokeless briquets, it became desirable to develop a quantitative measurement of smoke. Such a method of measurement permits the accurate determination of the smokiness of both naturally occurring coals of various volatile matter content and of briquets impacted from coal fines processed to various volatile matter content by the method herein described.

The Encyclopedia Britannica describes smoke as follows:

"Smoke is a general term applied to the visible exhalations from burning materials.

"Nearly all fuels consist essentially of carbon, hydrogen, oxygen and nitrogen, in various proportions and variously combined. In addition, they usually contain a little sulfur, while in solid fuels varying amounts of incombustible mineral ash are also incorporated. If complete combustion were always attainable, no fuel would emit smoke, the final products in such an ideal case being limited to carbon dioxide, water vapor, and free nitrogen, all quite innocuous gases, and invisible unless the water vapor condenses to a cloud of steam. There would, however, if sulfur were present, also be produced small quantities of sulfur dioxide gas, which, also invisible, has a pungent smell, and in contact with air and moisture tends rapidly to be converted into a corrosive acid; while the mineral constituents would remain unburned in the form of ash.

"To achieve such finality it is necessary only that a fuel should be brought into contact with enough air for full oxidation while maintained at a temperature sufficiently high for combustion to take place. These conditions, although apparently simple, are by no means easy to realize, and in practice some proportion of a fuel always eludes complete combustion. The unburned products vary widely in amount and in composition according to the nature of a fuel and the manner of its use, being in some circumstances inappreciable, in others very large. They are moreover not necessarily in the form of smoke, since with insufficient air

[1] Piersol, R. J., Briquetting Illinois coals without a binder by compression and by impact: Illinois State Geol. Survey Report of Investigations No. 31, 1933.
[2] Part I of this report, pp. 7-30.

carbonaceous materials may emit gaseous intermediate products such as carbon monoxide and unsaturated hydrocarbons; but whether or not smoke is produced, incomplete combustion is always indicative of thermal loss.

"Thorough admixture with air is relatively easy to secure in the case of gaseous fuels, which in properly constructed and properly adjusted burners produce neither smoke nor other unburned products in appreciable quantity. An inadequate air supply, however, or the chilling or smothering of the flames, may result in the evolution of unburned gaseous products, including carbon monoxide and oxides of nitrogen, both highly poisonous; or in extreme cases may even cause the deposition of soot.

"Owing to the relatively high density of solid fuels, the problem of bringing them into contact with sufficient air for complete oxidation is greatly intensified, and, even with an air supply far in excess of that theoretically required, perfect combustion cannot in practice be counted upon.

"With bituminous coals, smoke production to a greater or lesser degree, according to the circumstances, is practically unavoidable; for such coals are subject to decomposition at temperatures below the ignition point, with the evolution of combustible gases and condensable tarry vapors. These are of so complex a character, and under the action of heat are subject to such complicated chemical changes, that although the more readily ignitible constituents may burst into spasmodic flames, others almost inevitably escape unburned. Coal smoke consists of such unconsumed distillation products, in association with carbon and tarry matter condensed by premature chilling of flame, together with dust and ash entrained by the upward rush of hot air and gases from the grate. Some of this settles on the walls of the flue as soot; the remainder is carried out through the chimney into the atmosphere with the excess air and gaseous products of combustion, both burned and unburned."

SCOPE OF INVESTIGATION

The present investigation included, first, a survey of previous methods used for smoke determination; second, development of a laboratory method and equipment for determining the total amount of smoke emitted during the combustion of a small sample of fuel; third, standardization of equipment under most suitable conditions for testing; fourth, methods of calculating the smokiness of a sample of fuel in terms of a factor, referred to as the smoke index; fifth, the determination of the smoke index of naturally occurring coals of various volatile matter contents; and sixth, the determination of the smoke index of briquets impacted from Illinois coal fines processed to various volatile matter contents.

The method described in this report measures the total quantity of smoke produced by the combustion under standard conditions of a small weighed sample of fuel; previous methods have determined only the gross effect of smoke produced in commercial furnaces.

The present equipment is so designed that the total smoke liberated, under controlled conditions, in combustion of a small sample of fuel of known

weight, passes through a tube for light absorption where the smoke density is measured at regular time intervals by means of a photo-electric cell. The galvanometer deflections produced by the photo-electric cell are used to calculate the smoke index of the sample.

In order for such a method to be of service it is necessary that results be reproducible within the desired degree of accuracy. Also, it is desirable that the equipment be so standardized that comparative results may be obtained in other laboratories. As is well known, coal does not possess a simple chemical composition, and it is therefore difficult, if not impossible, to use coal as a standard for calibration of smoke measurement equipment in various laboratories. Thus it was necessary to seek a material which might serve as a suitable standard for this purpose.

Further, it is desirable to use an expression which signifies the total amount of smoke liberated in burning a unit quantity of fuel under standard conditions of testing. For this, the term smoke index is used. It is arrived at by multiplying the average percentage absorption of light by the time (in seconds) of smoke emission of one gram of fuel. As shown later, the value of the smoke index may be calculated algebraically or determined graphically.

SUMMARY OF FINDINGS

The equipment developed for the measurement of smoke index consists of an electric muffle furnace in which the sample of fuel may be burned at a certain temperature and with a specified supply of air. All the smoke produced is drawn through an absorption tube at a constant rate of flow and the smoke density is measured by its absorption of a beam of light, of known intensity, passing lengthwise through the tube. The amount of light thus absorbed is determined by a Weston Photronic cell and a galvanometer, the readings being taken at regular intervals.

Smoke equipment of this type is not described in the literature, so far as known, and therefore it is impossible to calibrate it against any previous standard. Thus it was desirable to devise some method by which it, or any similar equipment built by another laboratory, may be calibrated against a material having a constant smoke index for specified conditions of burning.

It is found that naphthalene, when burned at a furnace temperature of 90°C. (10°C. above its melting point) in a container of suitable size and shape, possesses a constant smoke index. Naphthalene is obtainable in pure form as moth balls. Thus any duplicate equipment for measuring smoke index of coal or other fuel may be calibrated by using naphthalene as a standard material.

The smoke index and the rate at which the smoke is emitted are influenced greatly by the conditions under which the fuel is burned. In order to

find the most suitable temperature for measuring the smoke index of coal, the range from 600°C. to 1000°C. was investigated. Lower temperatures were not investigated since some bituminous coals have ignition temperatures approaching 600°C. The data obtained indicated that the most reproducible results are obtained at 600°C. Therefore this temperature was selected for use in all tests.

For the same reason, the influence of air supply on the smoke index was investigated. With an air flow less than 4 cubic feet per minute an excessive quantity of soot was deposited on the inner surfaces of the equipment. Data showed that reproducible results are obtained with an air supply of 4 cubic feet per minute.

Also a series of tests were made to determine the degree of reproducibility on as nearly identical samples of coal as were obtainable, these samples differing slightly, however, in weight. The time required for combustion indicated a high degree of uniformity of the samples. The results showed a maximum deviation from the average smoke index of 6.3 per cent and a mean deviation of 3.7 per cent.

The results of the investigation show that there appears to be a direct proportionality between the smoke index and the percentage of volatile matter in the Illinois and West Virginia coals investigated.

For the Illinois coal fines processed by the method herein described, there is also a linear relationship between the smoke index and the percentage of volatile matter in the partially volatilized product, although the decrease in the smoke index is far more rapid than the decrease in volatile matter. Thus a smokeless briquet may be prepared with a much higher volatile matter content than that of a naturally occurring smokeless coal.

ACKNOWLEDGMENTS

Mr. J. M. Nash, Physics Assistant of the Survey staff, carried out the larger part of the experimental work with assistance furnished by the Civil Works Administration as follows: Dr. F. W. Cooke, Physicist, Dr. J. J. Gibbons, Physicist, Dr. R. W. Tyler, Physicist, and Mr. P. G. Jones, Physics Assistant. Mr. H. C. Roberts, Physics Assistant of the staff, designed and constructed the equipment. Dr. C. F. Fryling, Chemist, Non-fuels Division of the Survey, suggested the use of naphthalene for standardization. Dr. O. W. Rees, Associate Chemist, Analytical Division, of the Survey, supervised the chemical analyses. The Peabody Coal Company furnished the sample of coal.

CHAPTER II—PREVIOUS METHODS OF SMOKE DETERMINATION

Previous methods of smoke determination have included smoke density measurements, analytical measurements, and smoke recorders. Also furnace air drafts have been controlled by photo-electric relays located in the smoke stacks.

SMOKE DENSITY MEASUREMENTS

One of the most common methods for measuring smokiness has been the determination of the optical density, or opacity, of the smoke as it issues from the stack. This method and all its modifications have the limitation of measuring only the density of a continuous column of smoke, thus failing to determine the total amount of smoke. However, this method gives valuable information in that the density of smoke liberated from various fuels, or the same fuel at various stages of combustion, may be compared.

By far the most widely used of these is the Ringelmann method[1] of determining the density of smoke. This method, which was devised by Professor Ringelmann, includes the use of a set of six comparison charts and a method of calculation. The six charts (Fig. 1) represent different degrees of gray, ranging from white to black. This method is described in the smoke abatement report of the Chicago Association of Commerce Committee of Investigation on Smoke Abatement as follows:

"Each chart is numbered for reference purposes, to-wit: No. 0—100% white; No. 1—80% white and 20% black; No. 2—60% white and 40% black; No. 3—40% white and 60% black; No. 4—20% white and 80% black; No. 5—100% black. The white on the chart is the clear background of the white paper on which the chart is made, and the black is in the form of lines in cross-section, for charts Nos. 1, 2, 3, and 4, the width of the lines being such that the proportional amount of black is shown. The whole surface of chart No. 5 is black.

"By placing the Ringelmann scale far enough from the eye, the cross-section lines on the four charts, Nos. 1, 2, 3, and 4, become diffused to the eye and appear as different shades of gray, while the white chart, No. 0, and the black chart, No. 5, appear unchanged in color.

"Comparative observations of smoke by the Ringelmann scale are made by placing the scale of six charts at the proper distance between the observer and the

[1] Smoke Report, Chicago Association of Commerce Committee of Investigation on Smoke Abatement and Electrification of Railway Terminals.

smoke to be observed, with a clear background for the smoke, and with no direct rays of the sun entering the eye of the observer. The color of the smoke emitted is then compared with the colors of the six charts—

"The formula for computing the per cent of density of smoke is

$$\frac{\text{Smoke units x 20}}{\text{Stack minutes}} = \text{per cent of density}$$

"A 'stack minute' corresponds to the observation of one stack for one minute . . . A 'smoke unit' corresponds to the emission of No. 1 density of smoke for one minute, or its equivalent."

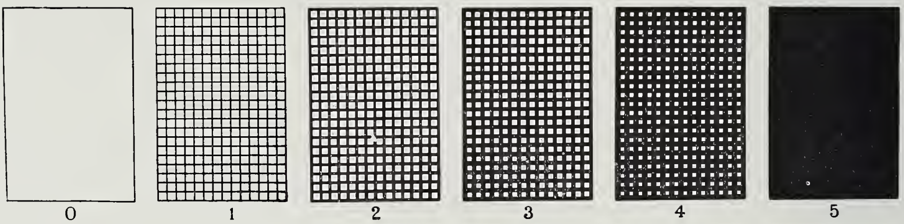

Fig. 1.—Ringelmann Chart of Smoke Densities.

This method evidently is limited to data on the gross amount of smoke passing through a stack. Therefore, it gives pertinent information as to optimum conditions of combustion, but, of necessity, it cannot give a quantitative measurement of the amount of smoke liberated per unit weight.

ANALYTICAL METHODS

A number of tests involving physical and chemical analyses have been developed. For determining the amount of solids in smoke, and extracting these solids for testing purposes, one method is as follows. The stack is fitted with a sampling tube into which part of the smoke is drawn, by means of a vacuum pump, through a fine paper filter which retains the solid part of the smoke. This solid part is weighed, screened to determine particle size, and then analyzed chemically. Solid particles larger than 20-mesh are classed as "coarse cinders," those between 20-mesh and 200-mesh, as "fine cinders," and those passing a 200-mesh screen are called "fuel dust." The solids are then analyzed to determine amounts of tarry matter, combustible matter, mineral matter or ash, and the sulfur compounds.

The gaseous part of the smoke, after having had the solids filtered out, may be analyzed to determine the amount of carbon dioxide, carbon monoxide, oxygen, nitrogen, sulfur compounds, etc., that may be present. Standard methods of gas analysis may be used for this. For convenience, the Hayes portable gas-analysis outfit is often used.

These chemical and physical tests give excellent and accurate information on the character, especially the destructive character and offensiveness, of the

smoke produced. They require complicated and expensive apparatus with readings made by several operators at specified intervals and are consequently expensive. Also the results are similar to those obtained by smoke charts in that information is lacking as to the amount of smoke produced per pound of coal.

SMOKE RECORDERS

In many industrial districts adjacent to residential areas, ordinances are enforced which limit the density of smoke emitted by stacks. It is impossible to station an observer to take readings continuously at each stack, and to

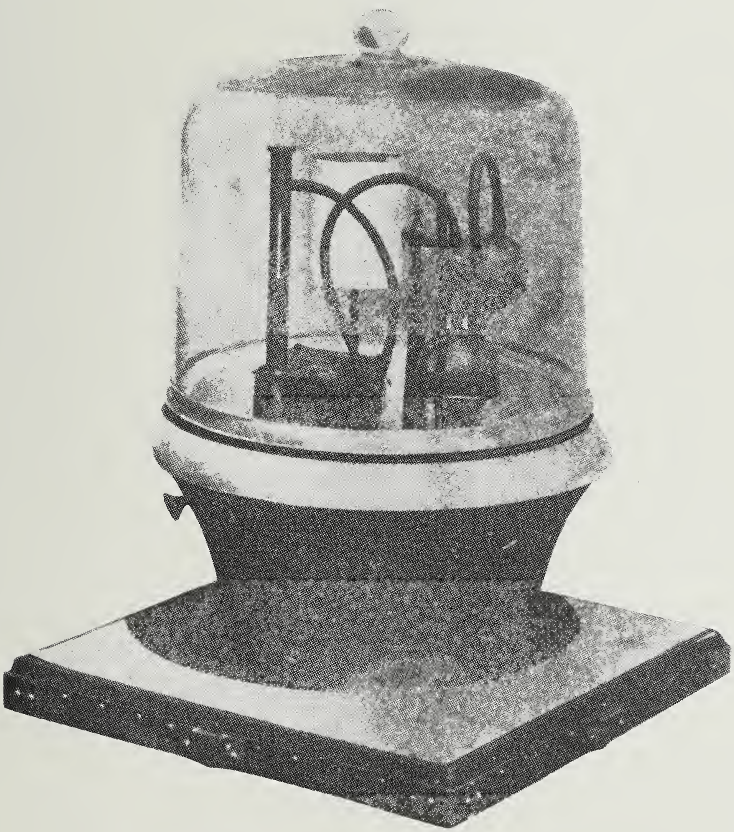

Fig. 2.—Hamler-Eddy Smoke Recorder.

solve this problem, smoke recording devices have been constructed, such as the Hamler-Eddy smoke recorder (Fig. 2). In this instrument, a small amount of smoke is being constantly drawn from the stack, dried, and forced in a fine jet against the white paper surface of a revolving drum to which some

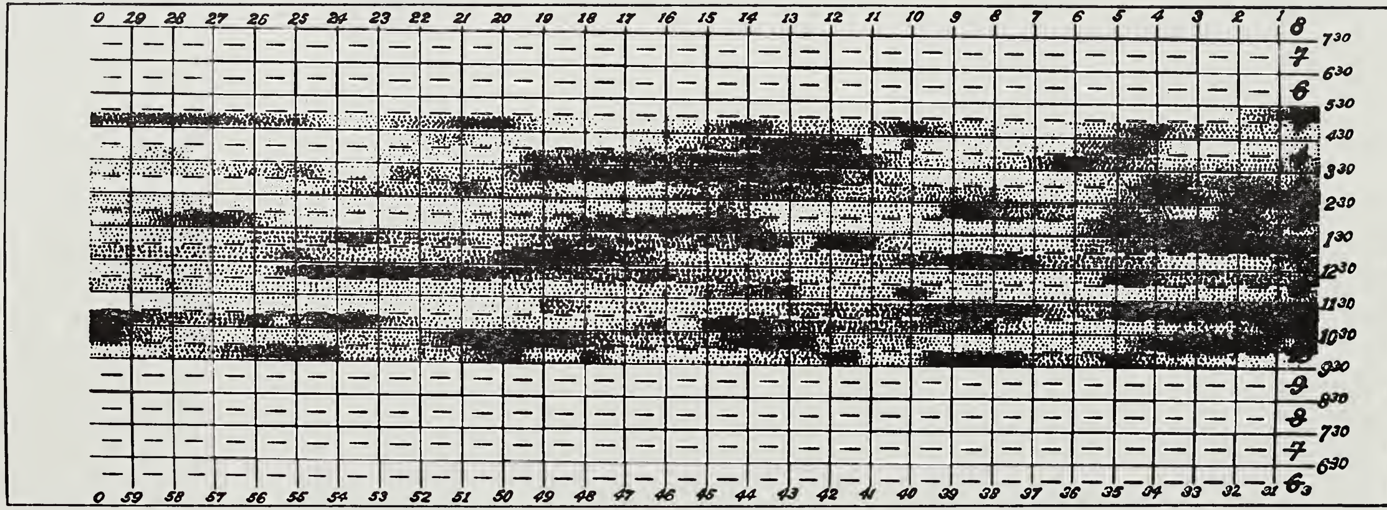

Fig. 3.—Chart Made by Hamler-Eddy Smoke Recorder.

Smoke Record Chart for Fourteen Hours

Read from right to left and from bottom upwards.
The figures on the right are the hour and half hours and those on the top and bottom are minutes of the hour.
The space below the *full line* is for the first half of the hour and that above the line is for the last half of the hour.

of the solids in the smoke adhere, giving a line of variable density, its density being proportional to the opacity of the smoke.

A more recent type of smoke recorder involves the use of the photo-electric cell set in the stack to determine continuously the density of the smoke. With the advent of the smoke abatement movement, a number of such devices have been installed in commercial plants for stack regulation. These instruments are all of the same general type although they differ somewhat in detail. A lamp giving a constant intensity of illumination is set inside, in the wall, or outside the stack, and its beam is directed across the stack, through the path of the smoke, to a photo-electric cell near the opposite wall of the stack. All or a definite fractional part of the smoke passing through the stack is allowed to obscure the beam of light, the density fluctuations of the smoke thereby causing corresponding fluctuations in the current generated by the photo-electric cell. The output of the cell may be amplified and the fluctuations recorded on a moving drum thus giving a continuous record of the smoke density. Or the cell may be connected to a sensitive relay which will automatically sound a warning signal when the smoke density exceeds the specified value.

All of the methods referred to above are intended for measurement of the density of smoke ejected into the atmosphere by a smoke stack. None of them gives a quantitative measurement of the amount of smoke given off by a given quantity of fuel while it is being burned to ash. Therefore, these methods are of little value in determining the inherent smokiness of a fuel, under a given set of conditions.

CHAPTER III—DESCRIPTION OF THE SMOKE INDEX METHOD

The smoke index method is a quantitative test which may be performed on any sample of fuel of any convenient weight. However, the present equipment has been developed for a sample of approximately one gram. The possibility of using a small sample has its advantages. For instance, tests may be made on one coal ingredient only, such as clarain; or tests may be made to determine the effect of size and shape of small particles (or to determine the effect of texture of a lump sample on the smoke produced, small lump samples may be used). In this study, the samples used were all cut to the same size and shape on a carborundum saw, their weights being slightly variable.

In direct contrast to all known previously used methods of measuring smokiness, the smoke index method measures the total amount of smoke produced. Every particle of smoke passes through the smoke absorption tube, requiring an appreciable time for its passage. The use of the smoke index method eliminates two defects of the previously used methods: i.e., the necessity for the by-passing of a small fraction of the total smoke through the apparatus; and the irregularities in smoke emission due to the periodic addition of fresh coal under ordinary firing conditions.

Since all the smoke passes through the absorption tube in the smoke index equipment, it is subject to measurement at every stage of burning, from before the time of ignition to complete ashing, if desired. The excessively large amounts of smoke liberated in the initial stages of burning are manifested, not being masked as they would be if other fuel in advanced stages of combustion were present at the same time. In fact, observed data are plotted so that they show clearly the relation of smoke produced to the stages of combustion.

The sample to be treated is placed in a muffle furnace, where conditions of temperature and air supply may be accurately controlled. The heat capacity of the furnace is sufficiently large that the heat which the small sample gives off while burning does not raise the temperature of the furnace appreciably. The present furnace weighs about 30 pounds, being constructed of materials which have an average of about 0.2 specific heat. Thus the heat capacity of the furnace is equivalent to that of 6 pounds of water. The calorific value of bituminous coal is usually less than 15,000 B.t.u. Therefore the combustion of a one-gram sample of coal liberates not more than 33 B.t.u.

which would raise the temperature of the furnace about 5.5°F. or 3.0°C. The sample is thus exposed to almost constant furnace temperature (within 3.0°C.) throughout all stages of combustion.

The smoke, as it issues from the burning sample, is drawn through the absorption tube. A beam of light is constantly passing axially along this absorption tube, striking the light-sensitive photo-electric cell which is connected to a galvanometer. When no smoke is present to obscure the light beam, the galvanometer shows a maximum deflection. As smoke enters, it partially intercepts the light falling on the photo-electric cell, and the amount of obscurity, or the smoke density, may be calculated from the change in the galvanometer reading. That is, the amount by which the galvanometer reading is decreased, in per cent, represents the proportion of light intercepted by the smoke in the absorption tube, in per cent. This in turn is in direct ratio to the amount of smoke present. If these individual smoke-density percentages, taken at regular intervals, are averaged, the result is the average per cent smoke density produced during the entire period of combustion. If this average is multiplied by the time required for combustion, in seconds, the total amount of smoke given off by that sample, in units of percentage smoke density and seconds time, is obtained. And if this total amount of smoke is divided by the weight of the sample used, the amount of smoke given off per gram of fuel, in terms of percentage smoke density and seconds time, is obtained. This value is called the smoke index.

The actual value of the smoke index for any particular sample may be obtained either by a graphical method or by a numerical calculation. Both methods are described herein.

CHAPTER IV—EQUIPMENT AND PROCEDURE

A detailed description of equipment and procedure is here included in order to permit other investigators to duplicate smoke index determinations.

EQUIPMENT

The essential equipment consists of an electric muffle furnace, a tube for light absorption by the smoke, a source of air supply, means for drawing the smoke through the absorption tube, a source of constant illumination, a photoelectric cell, and a galvanometer.

Furnace.—The electric muffle furnace (Fig. 4) constructed for use in the investigation consisted of a three-inch inside diameter alundum tube, A,

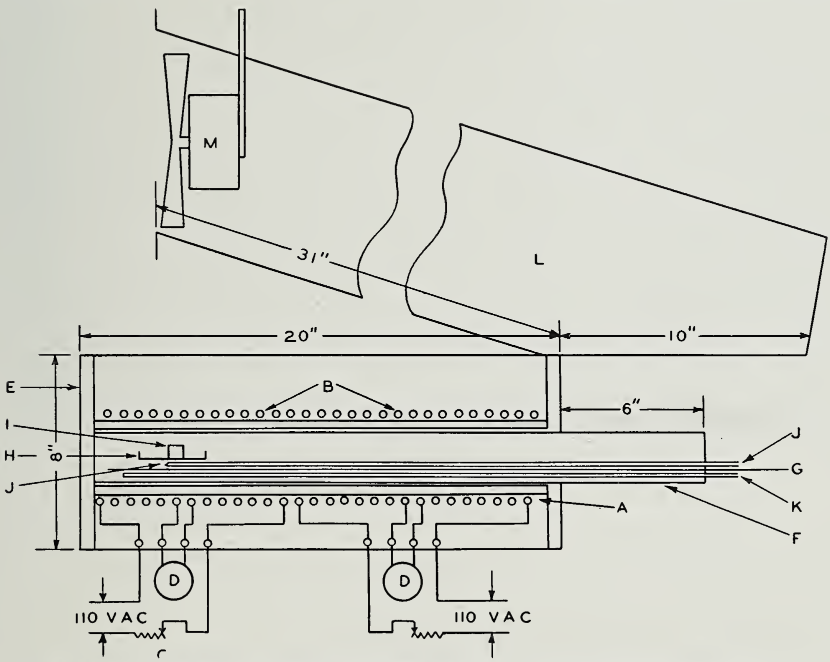

Fig. 4.—Diagram of Combustion Furnace. (Illinois State Geol. Survey Report of Investigations 37, Fig. 15, p. 69, 1935.)

18 inches long, wound with two heating elements, B, of No. 19 "Chromel" wire and each having a resistance of 15 ohms. Each of the two elements had a separate controlling rheostat C, and an ammeter D, in series with it, so that

the temperatures of the front and rear parts of the furnace could be controlled separately, if desired.

In the naphthalene standardization tests, the two heating elements were connected in series, in order to secure the low temperature of 90°C. In all the smoke index tests on coal, the two heating elements were connected in parallel, so as to make possible the higher furnace temperatures from 600°C. to 1000°C. In this case the same amount of current was passed through each coil, thereby insuring uniform temperature along the length of the furnace.

The alundum tube, with the heating coils, was given a coating of alundum cement about ¼-inch thick, fired, and then placed in a steel and transite case E, 8 inches square and 20 inches long, packed with "Sil-o-Cel". A steel tube, F, 2½ inches inside diameter and 26 inches long, was fitted into the alundum muffle to protect it and to increase the heat capacity of the furnace and thereby minimize small fluctuations in temperature.

A steel tray G, 1⅞ inches wide, ⅛-inch deep, and 30 inches long, was used to carry the container H, in which the sample I, was placed. The thermocouple J, was mounted in the tray with its junction directly under the sample container. The thermocouple leads extended to a potentiometer near the open end of the furnace. Air was introduced into the furnace through a small iron pipe K, leading to the back of the furnace, passing along the bottom of the muffle beneath the tray. The amount of air admitted to the furnace was measured by a calibrated differential manometer of orifice type.

Absorption tube.—The smoke given off by the burning sample is drawn from the mouth of the furnace A, through the absorption tube B, by a com-

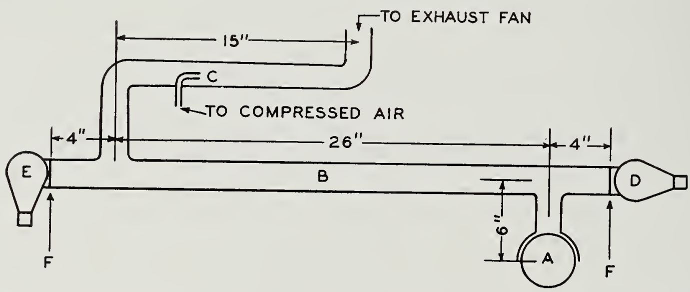

Fig. 5.—Photo-Electric Unit For Determination of Smoke Index.

pressed air aspirator C (Fig. 5). This tube is 34 inches long and 1⅜ inches inside diameter, and its inner surfaces are blackened. At the end of the absorption tube nearest the furnace there is mounted a 15-watt, 110-volt A. C. inside-frosted incandescent bulb D, in the sleeve, in such a manner that the rounded surface of the bulb is 1 inch from a glass window F, closing the end of the absorption tube. On the other end of the absorption tube is a

similar sleeve in which the photo-electric cell E is mounted. As the smoke passes through the absorption tube the beam of light from the incandescent bulb, D, is partially obscured, the intensity of the transmitted light being measured by the photo-electric cell E. In the direction parallel to the axis of the tube and with no smoke present, the intensity of illumination on the photo-electric cell is 0.75 foot-candle. The ends of the tube are closed by the thin glass plates F, which are placed 4 inches from the inlet and outlet of the

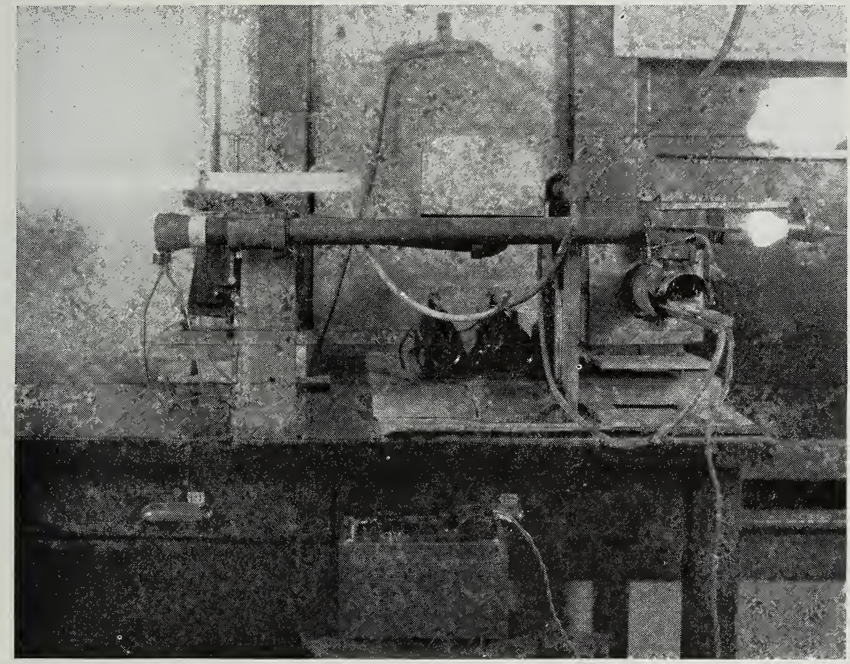

Fig. 6.—Assembled Smoke Index Apparatus.

absorption tube. These windows may be cleaned as required, but, due to their position, remain fairly clean throughout one test. The assembled smoke index apparatus is shown in figure 6.

The photo-electric cell used in this investigation was a Weston Photronic cell, Model 594. This cell, while not as sensitive as some of the alkali cells, is very durable. It was connected in series with a 3000 ohm resistance and a D'Arsonval type galvanometer (sensitivity = .00082 milli-amperes per millimeter at a distance of 1 meter).

PROCEDURE

Before using the smoke index equipment, it was necessary to calibrate the photo-electric cell, the incandescent lamp, and the differential manometer.

Calibration of apparatus.—The incandescent lamp, used as a light source, was an ordinary commercial 15-watt General Electric bulb. Its candlepower was determined, using a Bunsen photometric bench and a standard lamp. The candlepower of the incandescent bulb, in the direction along its axis from its rounded end, was found to be 20.4.

Table 1.—Calibration Data for Weston Photo-Electric Cell

(Data for Fig. 7)

Deflection (millimeters)	Intensity (foot-candles)
250	.729
234	.695
214	.632
193	.573
174	.528
157	.481
144	.445
130	.410
121	.381
114	.354
105	.331
99	.307
93	.289
87	.272
83	.256
79	.241
75	.227
72	.214
69	.204
67	.192
64	.183

A part of the surface of the incandescent lamp is obscured by the sleeve of the absorption tube when the lamp is in place in the apparatus. A determination of the light intensity at the photo-electric cell end of the absorption tube was made entirely separate from other calibrations. The galvanometer deflection from the photo-electric cell was 257 mm. with the lamp in place and supplied with an exact potential of 110 volts. The intensity of illumination on the photo-electric cell necessary to produce this deflection was found to

be that given by the standard lamp, 46.97 candlepower, at a distance of 7.91 feet. The intensity of illumination was thus calculated, by dividing 46.97 by 7.91 squared, to be 0.75 foot-candle.

Also the photo-electric cell was calibrated, using the above standard lamp and varying the intensity of illumination on the light-sensitive surface of the photo-electric cell by placing the standard lamp at various distances. From the known candlepower of the standard lamp, it is possible to calculate the intensity of illumination (in foot-candles) which varies as the reciprocal of the square of the distance between the lamp and the surface of the photo-electric cell. The data for the calibration of the photo-electric cell are recorded in Table 1 and the corresponding calibration curve is plotted (Fig. 7).

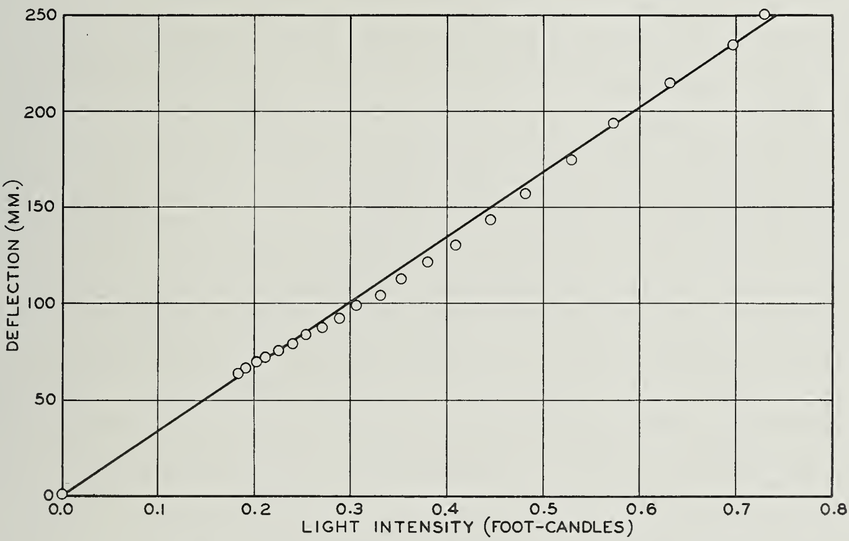

Fig. 7.—Calibration Curve For Weston Photo-Electric Cell.

The intensity of illumination used in the investigation varies from 0.75 foot-candle with no smoke to zero with complete absorption of light by smoke. For this range it may be seen that the calibration curve is approximately a straight line.

The differential manometer was calibrated against a Sargent wet test gas meter (Fig. 8).

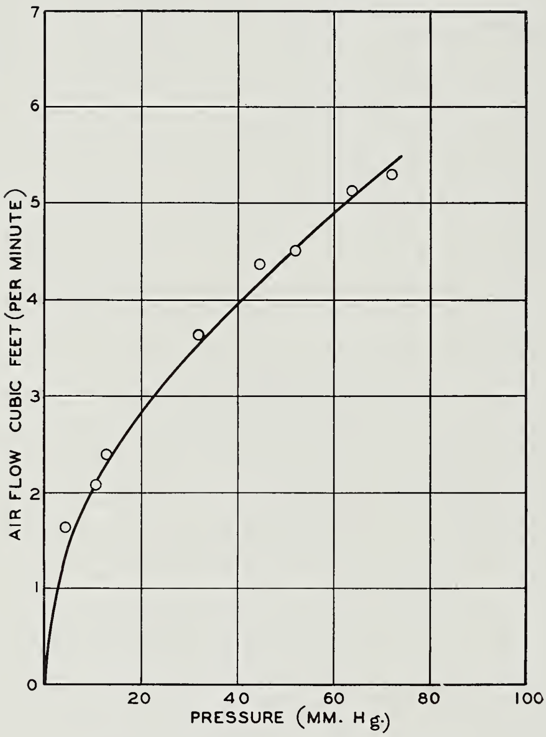

Fig. 8.—Calibration of Manometer.

Standardization of equipment with naphthalene.—In order to provide a means for determining the reproducibility of smoke index results, it was necessary to standardize the equipment by the smoke index of some common substance which would be of the identical constituency wherever obtained. Coal is heterogeneous, and hence cannot be used as a standard material from laboratory to laboratory. The material finally selected was naphthalene, the reason for its choice being that it may be obtained anywhere in a high degree of purity in the form of moth balls. An index to the purity of naphthalene is its melting point. For the desired degree of purity necessary for reproducibility of smoke index, the melting point of naphthalene should be between 80.0 and 81.5°C. Moth balls were purchased from three different sources and their melting points determined.

Table 2.—Melting Point of Naphthalene (Moth Balls)

Laboratory number	Sample number	Melting point °C.
0-968	N-1	80.5 to 81.5
0-969	N-2	80.5 to 81.0
0-970	N-3	80.5 to 81.0

The results, given in Table 2, show practically no variation. When burned, naphthalene gives off a very dense, black smoke and the amount per unit weight can be easily and accurately determined by the smoke index method, using a certain controlled set of burning conditions.

In determining the smoke index of naphthalene, samples exactly one gram in weight were used. The furnace was maintained at a temperature of 90°C., which is approximately 10°C. higher than the melting point of naphthalene. The air supply was held at a rate of flow of four cubic feet per minute. The weighed samples of naphthalene were placed in the container and put into the furnace and allowed to melt. As soon as the sample was entirely melted, the container was drawn to the mouth of the furnace and the naphthalene ignited by means of a Bunsen blue flame. Immediately upon ignition the container, holding the burning naphthalene, was pushed back to the middle of the furnace and galvanometer readings started. In making these tests the size and shape of the container was found to be very important as regards the rate of burning of the naphthalene. It was desirable to choose the type of a container which would give about the same rate of burning as a one gram sample of coal so that, during any stage of burning, the light passing through the absorption tube would not be completely obscured by the smoke. Since the smoke index method is based on the measurement of percentage light absorption of smoke, it is evident that the density of the smoke

to be measured must be less than that necessary to give complete absorption of light. The container which was eventually found to meet these conditions was made from nickel steel, cylindrical in shape, 1 inch inside diameter, 9/16 inch inside depth, with 1/8 inch wall and 1/32 inch bottom. As stated previously, the container was placed about half way back in the furnace for the tests. The bottom of the container was 3/4 inch from the bottom of the furnace tube.

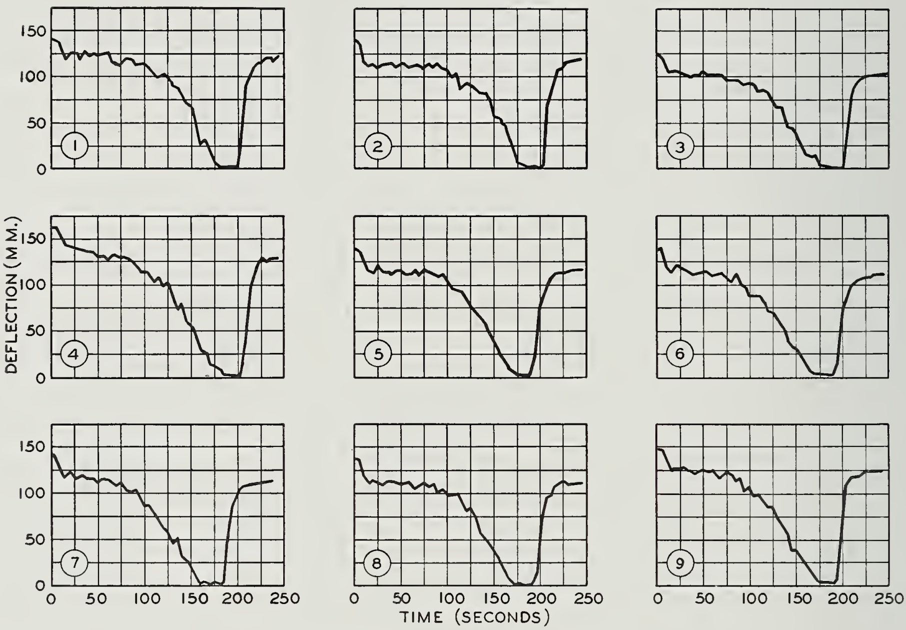

Fig. 9.—Naphthalene Tests.

A series of nine duplicate smoke index tests was made, using 1-gram samples of naphthalene, at a furnace temperature of 90°C., an air supply of 4 cubic feet per minute, following the procedure described above. The data for this series of tests are shown in Table 3 (Fig. 9). Table 4 indicates the degree of reproducibility which can be secured with the apparatus at the present time. The average deviation from the average value was 3.1 per cent, the maximum deviation being 7.1 per cent.

TABLE 3.—STANDARDIZATION OF EQUIPMENT (NAPHTHALENE TESTS)

(DATA FOR FIG. 9)

Time (seconds)	Galvanometer deflections (millimeters)								
	1	2	3	4	5	6	7	8	9
0	141	137	128	162	141	138	138	136	147
5	140	136	124	162	137	141	141	138	148
10	130	116	106	150	124	120	125	120	137
15	118	111	106	143	116	113	117	110	123
20	127	114	106	141	114	122	120	115	129
25	127	110	104	139	122	119	116	113	126
30	118	113	101	138	115	116	118	110	126
35	129	......	99	135	115	114	118	114	124
40	122	114	102	134	114	112	116	114	124
45	126	110	103	134	117	114	116	114	120
50	123	113	107	130	116	112	113	112	125
55	125	116	102	131	112	115	115	113	124
60	126	111	101	129	113	110	115	111	124
65	116	112	100	134	117	113	111	105	119
70	114	110	100	130	111	113	108	109	117
75	114	110	98	130	119	109	112	111	123
80	120	115	97	129	115	103	103	108	121
85	119	110	98	125	112	111	101	110	114
90	113	115	96	121	110	101	102	100	116
95	113	109	92	114	111	98	95	104	102
100	113	107	94	114	103	89	86	97	108
105	111	99	92	113	96	88	86	98	97
110	104	101	85	105	95	89	78	99	99
115	99	87	86	108	92	83	74	91	92
120	101	93	84	99	86	72	64	82	86
125	99	90	76	101	78	70	60	84	86
130	91	87	67	85	72	62	46	75	74
135	88	83	66	74	65	57	52	61	67
140	78	81	48	80	55	42	34	53	58
145	72	74	46	61	47	33	28	47	39
150	68	56	40	55	40	30	16	44	39
155	47	56	31	42	25	24	8	30	31
160	28	48	19	28	21	16	3	22	23
165	32	32	15	27	11	7	3	9	14
170	21	19	15	14	7	4	0	5	5
175	7	8	6	12	4	2	2	2	2
180	4	5	3	9	3	1	1	2	2
185	1	2	0	3	3	1	5	1	1
190	1	1	0	3	4	1	55	1	1
195	3	1	0	2	24	16	91	7	7
200	2	0	2	2	82	74	105	60	65
205	30	6	36	2	99	95	108	93	110
210	90	70	77	46	109	103	110	96	117
215	106	96	94	100	115	106	111	108	117
220	114	109	98	122	114	109	113	111	119
225	114	111	100	126	114	108	113	112	122
230	118	115	102	124	115	109	114	110	123
235	120	117	102	127	117	111	114	111	123
240	117	118	102	129	117	113	114	112	124
245	123	119	103	128	118	112	......	112	124

Table 3.—Concluded.

Time (seconds)	Galvanometer deflections (millimeters)								
	1	2	3	4	5	6	7	8	9
Total	4563	4173	3759	4752	4382	4121	4094	4202	4564
Number of readings	50	49	50	50	50	50	49	50	50
A	91.3	85.2	75.2	95.0	87.6	82.4	83.5	84.0	91.3
B	132.0	128.0	115.5	145.0	129.5	125.0	126.0	124.0	135.5
X	30.8	33.4	34.9	34.5	32.4	34.1	33.7	32.3	32.6
T	245	245	245	245	245	245	245	245	245
S	7546	8180	8550	8453	7938	8355	8257	7913	7987
W	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
I (smoke index)	7550	8180	8550	8450	7940	8350	8260	7910	7990

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100$.
T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 4.—Standardization of Equipment (Naphthalene Tests)

Test number	Smoke index	Deviation from average	Per cent deviation from average
1	7550	—580	7.1
2	8180	+50	0.6
3	8550	+420	5.2
4	8450	+320	3.9
5	7940	—190	2.3
6	8350	+220	2.7
7	8260	+130	1.6
8	7910	—220	2.7
9	7990	—140	1.7
Average	8130	252	3.1

Procedure in making smoke index tests on coal.—In making smoke index tests to determine the total amount of smoke liberated in the burning of a given quantity of coal, either powdered or lump samples may be used. Powdered samples of coal will give more representative results if it is desired that the smoke index should be that of composite coal, but lump samples are essential if the effect of the texture of coal on its smokiness is to be considered. Furthermore, the burning of lump samples more nearly approaches the household use of coal. Lump samples of coal were therefore used for smoke index tests made in this investigation.

In order to secure duplication of results, all samples were cut from one block of coal, selected on the basis of its apparent uniformity throughout. The most uniform available coal was a column sample of No. 5 seam from Mine No. 30 of the Black Mountain Corporation, Kenvir, Kentucky, with analyses as shown in Table 5. The banded constituent of this coal block was clarain throughout.

TABLE 5.—ANALYSIS OF COAL SAMPLE USED IN SMOKE INDEX TESTS

Laboratory number C-1047	"As received"	Air dried	Moisture-free	Moisture and ash free	Unit coal
Moisture	2.3	1.5	....	....	....
Volatile matter	35.6	35.9	36.4	37.4	....
Fixed carbon	59.6	60.1	61.1	62.6	....
Ash	2.5	2.5	2.5	....	....
Total sulfur	0.8	0.8	0.8	0.8	....
B. t. u	14,251	14,362	14,581	14,960	15,013

The samples were cut to approximately one–centimeter cubes with a carborundum saw. Because of the breaking of the coal upon cutting, it was not possible to get the small cubes of equal weight although most of them were approximately so. Each sample was accurately weighed before being tested.

The procedure in making a smoke index test was to have the furnace at the desired temperature, the rate of air flow being set at some given value, and then introduce into the furnace one of the small lump samples. The sample was placed on a small shallow nickel dish H (Fig. 4), which permitted a free circulation of air around the coal. The dish was placed on the furnace tray G, which was pushed into the furnace so that the sample, when burning, occupied a position about half way back.

Since the lowest temperature (600°C.) used in making smoke index tests was well above the ignition temperature of Illinois coals (maximum recorded value of ignition temperature of Illinois coals being 558°C.[1]), the sample started to smoke soon after being put in place. Galvanometer readings were taken at five-second intervals starting the instant the sample was placed in the furnace. They were continued until the sample stopped smoking as evidenced by the change from a yellow flame to a blue flame and also by the return of the galvanometer deflection to an approximately constant value.

[1] Arms, R. W., The ignition temperature of coal: Univ. of Illinois Eng. Exp. Sta., Bull. No. 128 (1922).

Graphical method of calculating smoke index.—A convenient method for evaluating smoke index data is to plot the densities of smoke as ordinates and the intervals of combustion as abscissae, the enclosed area representing the total amount of smoke produced. Figure 10 shows a smoke graph where actual galvanometer deflections are plotted as ordinates (zero deflection representing no light passing through the absorption tube, and initial deflection no

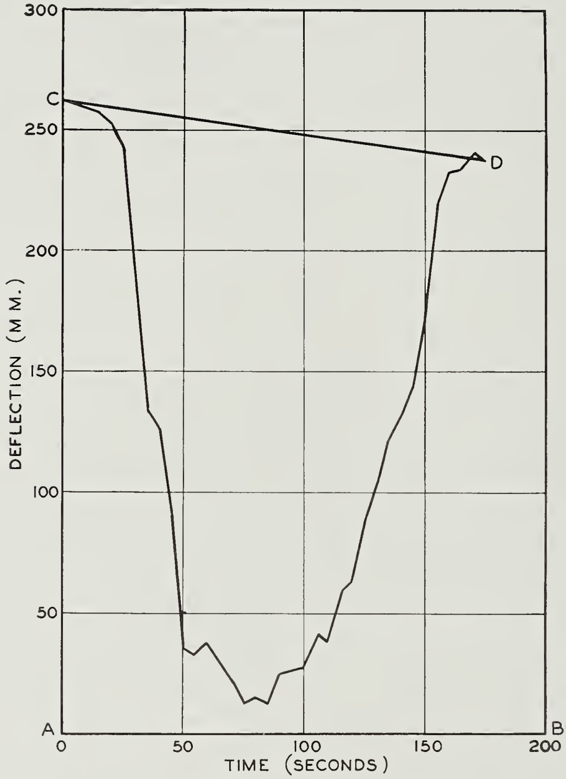

Fig. 10.—Smoke Graph.

light absorption by smoke) and periods of combustion as abscissae. A straight line is drawn between initial and final galvanometer deflections, this decrease in deflection representing the slight increase in absorption of light by a small deposition of soot on the tube windows during combustion. Consecutive points on the graph are connected by straight lines, instead of by an average curve, since the fluctuations in the smoke produced are better measured in this way.

The actual galvanometer deflections are then converted from millimeters to percentage values. The maximum light and total darkness readings were taken as 100 and 0 per cent respective for each deflection. Table 6 lists the

actual experimental values of galvanometer deflections in millimeters (Fig. 10), the same galvanometer deflections in per cent, and corresponding smoke densities in per cent. Referring to figure 10, the galvanometer deflection in per cent for each point is determined by the ratio of the vertical distances between the zero-deflection line AB and this point, and between this zero deflection line and the datum line CD, through this point.

Table 6.—Graphical Method of Calculating Smoke Index

(Data for Figs. 10, 11, and 12)

Time (seconds)	Observed galvanometer deflection (mm)=A	Corrected initial galvanometer deflection (mm)=B	Percentage galvanometer deflection mm.=A/B x 100	Decrement in galvanometer deflection (mm)=B-A	Percentage decrement in galvanometer deflection $=\frac{B-A}{B} \times 100$
0	262	262.0	100.0	0.0	0.0
5	261	261.3	99.9	.3	.1
10	259	260.6	99.4	1.6	.6
15	257	259.9	98.9	2.9	1.1
20	252	259.3	97.2	7.3	2.8
25	241	258.6	93.2	17.6	6.8
30	196	257.9	76.0	61.9	24.0
35	134	257.2	52.1	123.2	47.9
40	127	256.5	49.5	129.5	50.5
45	90	255.8	35.2	165.8	64.8
50	36	255.1	14.1	219.1	85.9
55	33	254.5	13.0	221.5	87.0
60	38	253.8	15.0	215.8	85.0
65	29	253.1	11.5	224.1	88.5
70	22	252.4	8.7	230.4	91.3
75	13	251.7	5.2	238.7	94.8
80	16	251.0	6.4	235.0	93.6
85	13	250.3	5.2	237.3	94.8
90	25	249.7	10.0	224.7	90.0
95	27	249.0	10.8	222.0	89.2
100	28	248.3	11.3	220.3	88.7
105	42	247.6	17.0	205.6	83.0
110	39	246.9	15.8	207.9	84.2
115	59	246.2	24.0	187.2	76.0
120	64	245.5	26.1	181.5	73.9
125	89	244.9	36.3	155.9	63.7
130	103	244.2	42.2	141.2	57.8
135	122	243.5	50.1	121.5	49.9
140	130	242.8	53.5	112.8	46.5
145	145	242.1	59.9	97.1	40.1
150	172	241.4	71.3	69.4	28.7
155	219	240.7	91.0	21.7	9.0
160	233	240.0	97.1	7.0	2.9
165	234	239.4	97.7	5.4	2.3
170	240	238.7	100.0	0.0	0.0
175	238	238	100.0	0.0	0.0

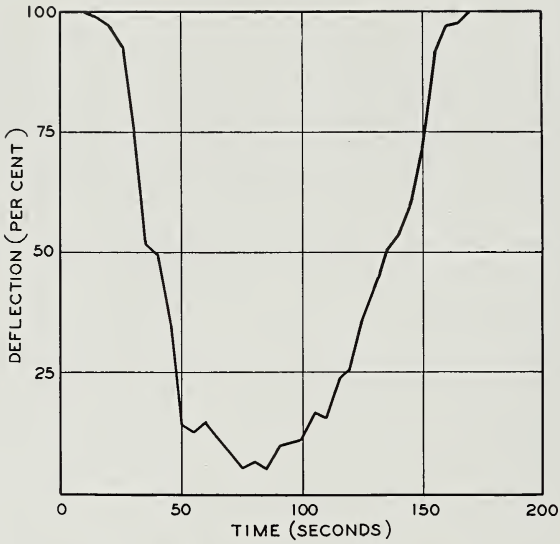

Fig. 11.—Smoke Graph.

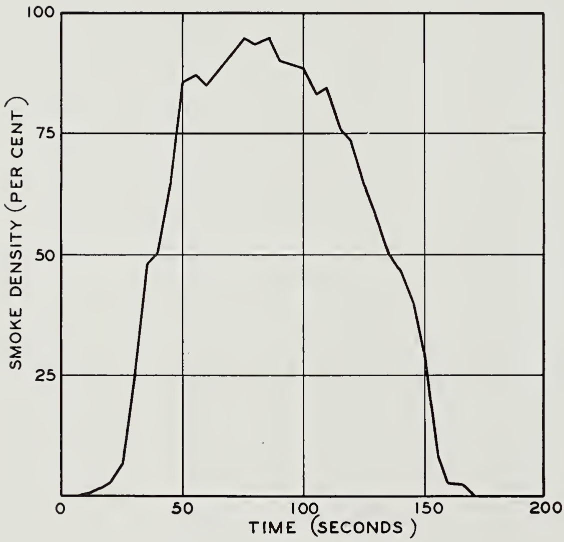

Fig. 12.—Smoke Graph.

Since the galvanometer deflection is a measure of the light transmitted rather than the light absorbed by the smoke, the smoke density percentage is the complement of the per cent galvanometer deflection (100 per cent minus the per cent galvanometer deflection).

Figures 11 and 12 show respectively graphs of galvanometer deflection in per cent and smoke density in per cent for the data recorded in Table 6. The smoke index of the sample in question can then be determined by measuring the area enclosed in its per cent smoke density-time graph by means of a planimeter, and dividing this area by the weight of the sample tested. Another approximate method might be to cut cardboard (made especially for such type of work) of the same shape as the per cent smoke density-time curves and weighing the cards. The ratio of the weight of such a card to the weight of a card consisting of the total area available in each instance, would be the average smoke density over the total time of combustion. This ratio (in terms of per cent) multiplied by the time of combustion and divided by the weight (in grams) of the sample tested, would give the smoke index.

In determining the smoke density-time graphs, a more exact method would be to use an automatic recorder. The expense of such an apparatus prohibited its use in this investigation. The areas generated by such a recorder might be evaluated by either of the above described methods.

Algebraic method of calculating smoke index.—Since the graphical method of calculating smoke index is subject to certain errors due to inaccuracies in measuring areas and, in addition, requires considerable time, it was thought advisable to use an algebraic or numerical method of calculation. All of the values of smoke index given in this report have been calculated by this method which is as follows: The sum of all the galvanometer readings over the period of smoke production is obtained, and the average galvanometer deflection is then calculated by dividing this sum by the total number of readings taken. Let this average galvanometer deflection be called A. The next step is to determine the mean value of the initial and final deflections. Let this mean value be called B. Then the average smoke density in per cent, during the total time of combustion of the sample, will be this mean deflection B, minus the average galvanometer deflection A, the difference being divided by the deflection B, and multiplied by 100; that is, average smoke density $(X) = \frac{B - A}{B} \times 100$. This value of average smoke density when multiplied by the total time of combustion T gives the value of the area S, enclosed by the smoke density-time curve, and the area S represents the total amount of smoke given off by the sample tested. Then in order to convert

to a common basis for comparison, this area S is divided by the weight of the sample W, which gives the smoke index I of the sample in units of per cent smoke density times seconds, per gram, or

$$I = S/W = \frac{\%\ \text{S. D.} \times T}{W}$$

This gives a simple and reliable method of calculating the smoke index of a fuel.

CHAPTER V—RESULTS

EFFECT OF AIR SUPPLY

It is well known that the rate and the degree of completeness of the combustion of any fuel depends in part upon the supply of oxygen (air) admitted into the combustion chamber. Therefore it was deemed advisable to investigate the effect of the air supply on the amount of smoke produced by the samples burned in the smoke index tests. To this end a series of 25 tests were made using air supplies of 2, 3, 4, 5, and 6 cubic feet per minute, five tests being made for each rate of air supply. The samples used in these tests were all cut from the same block of coal so that individual sample differences might be minimized. Their weights varied from 0.69 to 1.13 grams, most of them weighing between 0.90 and 1.10 grams. They were all approximately cubical in shape. The furnace temperature was held at 600°C., and the tests were carried out in the usual manner except that the rate of air supply was changed every five tests.

The data taken during these tests are tabulated in Tables 7, 8, 9, 10, and 11. At the bottom of each table are given the essentials of the calculations involved in determining the smoke indices. The last row of each table gives the value of smoke index for each of the five tests. These results are summarized in Table 12 (Fig. 13) which gives the individual values of smoke index for each of the five tests, for each air supply, and also the average value of smoke index for each air supply. They indicate that increased air supply decreases the amount of smoke given off. For air supplies less than 4 cubic feet per minute, there was quite an appreciable amount of soot deposited on the inner walls of the apparatus. For air supplies of 4 cubic feet per minute, or greater, this deposit was small.

The results indicate only a small variation of smoke index with variation of the air supply from 3 to 5 cubic feet per minute. Therefore for all subsequent tests the value of air supply was set at 4 cubic feet per minute, which is sufficiently high to avoid excessive soot.

Table 7.—Effect of Air Supply (2.0 Cubic Feet per Minute) on Smoke Index

Time (seconds)	Galvanometer deflections (millimeters)				
	1	2	3	4	5
0	243	231	248	224	219
5	241	221	240	223	213
10	237	209	239	218	197
15	228	165	237	206	178
20	201	121	233	181	152
25	185	98	226	153	123
30	131	72	210	105	142
35	87	19	190	24	31
40	58	11	150	19	6
45	59	17	26	13	11
50	67	19	29	16	13
55	22	26	22	18	18
60	5	77	17	19	26
65	14	66	47	14	24
70	29	86	57	15	17
75	46	50	91	41	56
80	16	33	56	45	109
85	15	35	50	36	185
90	59	99	57	34	201
95	99	147	61	88	207
100	163	137	29	130	209
105	181	141	39	139	....
110	183	160	74	106	....
115	186	175	95	157	....
120	202	199	149	206	....
125	221	212	202	210	....
130	235	216	223	....	....
135	....	218	225	....	....
140	....	219	....	....	....
145	....	....	....	....	....
150	....	....	....	....	....
Total	3413	3479	3522	2640	2337
Number readings	27	29	28	26	21
A	126.4	119.9	125.8	101.5	111.3
B	239.0	225.0	236.5	217.0	214.0
X	47.1	46.7	46.8	53.2	48.0
T	130	140	135	125	100
S	6123	6538	6318	6650	4800
W	1.03	1.04	1.03	1.06	.77
I (smoke index)	5940	6290	6130	6270	6230

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100.$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 8.—Effect of Air Supply (3.0 Cubic Feet per Minute) on Smoke Index

Time (seconds)	Galvanometer deflections (millimeters)				
	1	2	3	4	5
0	243	219	251	253	213
5	240	218	253	252	210
10	238	217	260	246	209
15	220	208	240	229	208
20	200	195	190	186	196
25	65	171	126	61	178
30	19	141	103	13	138
35	16	123	106	17	99
40	15	89	54	14	81
45	33	69	59	19	73
50	46	27	48	41	48
55	53	23	61	78	38
60	39	24	89	82	15
65	44	33	61	97	38
70	105	40	32	87	39
75	141	49	49	104	27
80	121	47	39	141	43
85	122	77	50	74	81
90	151	53	76	42	96
95	183	88	110	104	76
100	207	97	126	114	137
105	225	52	143	155	178
110	227	38	220	211	187
115	....	70	235	219	....
120	....	110	....	....	....
125	....	109	....	....	....
130	....	154	....	....	....
135	....	184	....	....	....
140	....	185	....	....	....
145	....	....	....	....	....
150	....	....	....	....	....
Total	2953	3110	2981	2839	2608
Number readings	23	29	24	24	23
A	128.3	107.2	124.2	118.2	113.3
B	235.0	202.0	243.0	236.0	200.0
X	45.4	46.9	48.9	49.9	43.3
T	110	140	115	115	110
S	4994	6566	5624	5739	4763
W	.99	1.13	.99	1.03	.76
I (smoke index)	5040	5810	5680	5570	6270

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.
T = total time in seconds.
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 9.—Effect of Air Supply (4.0 Cubic Feet per Minute) on Smoke Index

Time (seconds)	Galvanometer deflections (millimeters)				
	1	2	3	4	5
0	198	246	229	232	224
5	195	245	228	222	223
10	194	242	223	224	221
15	194	236	200	229	215
20	192	230	160	209	201
25	184	217	123	194	176
30	182	190	78	75	139
35	171	164	51	17	104
40	126	135	41	15	62
45	88	95	32	25	36
50	69	65	47	33	24
55	56	75	27	29	38
60	45	49	12	38	15
65	41	84	18	61	26
70	63	110	24	83	47
75	53	106	22	109	35
80	53	112	109	131	60
85	102	113	101	132	121
90	94	129	82	123	132
95	90	147	118	113	149
100	171	80	149	118	182
105	182	104	177	138	197
110	186	155	198	166	....
115	....	194	204	189	....
120	....	220	202	192	....
125	....	238	....	....	....
130	....	237	....	....	....
135	....	....	....	....	....
Total	2929	4218	2855	3097	2627
Number readings	23	27	25	25	22
A	127.3	156.2	114.2	123.9	119.4
B	192.0	241.5	215.5	212.0	210.5
X	33.7	35.3	47.0	41.6	43.3
T	110	130	120	120	105
S	3707	4589	5640	4992	4547
W	.69	.86	1.06	1.00	.80
I (smoke index)	5370	5340	5320	4990	5680

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100.$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample in grams.
I = smoke index = S/W.

TABLE 10.—EFFECT OF AIR SUPPLY (5.0 CUBIC FEET PER MINUTE) ON SMOKE INDEX

Time (seconds)	Galvanometer deflections (millimeters)				
	1	2	3	4	5
0	236	213	209	207	213
5	235	211	205	206	209
10	233	209	194	204	194
15	233	201	167	186	181
20	231	175	137	137	142
25	222	140	93	114	104
30	197	105	76	113	78
35	167	77	72	104	52
40	138	59	70	85	39
45	128	42	73	64	41
50	107	32	69	53	26
55	94	31	61	47	18
60	94	36	64	37	30
65	86	39	64	67	42
70	72	38	58	77	61
75	77	40	61	86	87
80	54	111	90	121	80
85	51	106	107	123	88
90	54	104	133	144	104
95	66	103	140	182	142
100	90	107	130	194	158
105	105	126	169	....	159
110	134	149	185	....	161
115	134	177	186	....	162
120	126	194	....	....	162
125	167	191	....	....	167
130	211	....	....	....	....
135	225	....	....	....	....
140	....	....	....	....	....
Total	3967	3016	2813	2551	2900
Number readings	28	26	24	21	26
A	141.7	116.0	117.2	121.5	111.5
B	230.5	202.0	197.5	200.5	190.0
X	38.5	42.6	40.7	39.4	41.3
T	135	125	115	100	125
S	5197	5325	4681	3940	5163
W	.96	.97	.94	.72	1.02
I (smoke index)	5410	5490	4980	5470	5060

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100.$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

TABLE 11.—EFFECT OF AIR SUPPLY (6.0 CUBIC FEET PER MINUTE) ON SMOKE INDEX

Time (seconds)	Galvanometer deflections (millimeters)				
	1	2	3	4	5
0	215	212	203	202	195
5	212	211	202	196	193
10	202	211	200	176	192
15	195	206	187	142	188
20	175	195	170	111	175
25	154	175	155	75	156
30	128	153	125	62	133
35	119	138	67	79	105
40	129	110	39	101	107
45	89	87	44	104	92
50	62	71	73	85	93
55	96	68	77	111	93
60	82	58	85	118	97
65	88	70	84	124	81
70	74	104	89	103	61
75	50	129	97	123	55
80	74	147	93	151	78
85	65	142	106	167	73
90	139	131	132	169	90
95	173	137	154	....	112
100	178	137	163	....	137
105	....	101	165	....	151
110	....	125	....	....	167
115	....	167	....	....	169
120	....	172	....	....	....
125	....	172	....	....	....
130	....	173	....	....	....
135	....	174	....	....	....
140	....	....	....	....	....
Total	2699	3976	2710	2399	2993
Number readings	21	28	22	19	24
A	128.5	142.0	123.2	126.3	124.7
B	196.5	193.0	184.0	185.5	182.0
X	34.6	26.4	33.0	32.0	32.0
T	100	135	105	90	115
S	3460	3564	3465	2880	3680
W	.87	.99	.91	.83	.91
I	3980	3600	3810	3470	4040

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

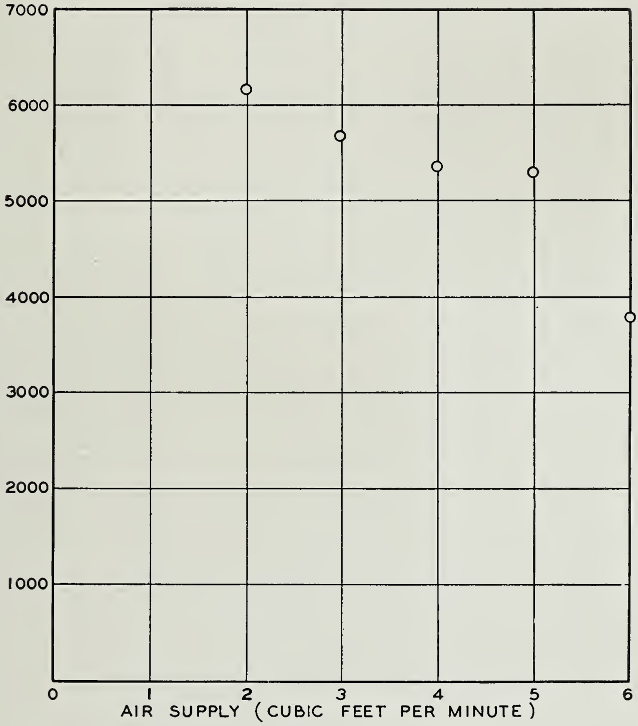

Fig. 13.—Effect of Air Supply on Smoke Index.

Table 12.—Effect of Air Supply on Smoke Index (Summary)
(Data for Fig. 13)
Smoke Indices

Test number	Air supply—cu. ft. per minute				
	2.0	3.0	4.0	5.0	6.0
1.	5940	5040	5370	5410	3980
2.	6290	5810	5340	5490	3600
3.	6130	5680	5320	4980	3810
4.	6270	5570	4990	5470	3470
5.	6230	6270	5680	5060	4040
Average	6170	5670	5340	5280	3780

EFFECT OF TEMPERATURE

The amount and character of smoke given off during combustion depends also, in part, on the temperature of the furnace. After determining a suitable rate of air supply, a series of tests was made to determine the temperature at which most accurate and reproducible results were obtained. The highest temperature of the upper portion of the bed of coal in a domestic furnace is from 600°C. to 1000°C.; accordingly, this range was investigated, in five steps of 100°C. each. Ten tests were made at each temperature, using duplicate samples. In order to minimize sample differences, all samples were taken from the same block of coal. The ignition temperature of the sample was well below the lowest temperature investigated. All samples were approximately cubical in shape, and their weights varied from 0.65 to 1.30 grams. For such small samples, the effect of such differences in size appears to be negligible.

The tests were carried out in the manner described previously, the air supply being held at a value of 4 cubic feet per minute. The temperature was raised 100°C. after every ten tests, starting at 600°C. and continuing to 1000°C. The data from these tests are shown in Tables 13, 14, 15, 16, and 17. At the bottom of each table are shown the calculations for smoke indices and the last row in each table gives the ten values of smoke index obtained for that specified temperature. Table 18 summarizes these results, giving the ten individual values of smoke index for each temperature used and, also, the average value of the smoke index for each temperature (Fig. 14).

The results of this series of tests show clearly a distinct decrease in smoke index with increasing furnace temperature, the average smoke index for 600°C. being 6390 and for 1000°C. being 2150, which is only one-third as great. This decrease takes place in a fairly uniform manner, although it is less pronounced in the middle than at the ends of the temperature range.

As regards the individual values of smoke indices, Table 18 shows that by far the most reproducible results were obtained at a temperature of 600°C. Since the values of smoke indices are much smaller at higher temperatures, any errors caused by irregularities in combustion will cause a greater per cent error. The temperature of 600°C. was selected for all tests since it gives the most reproducible results.

Table 13.—Effect of Temperature (600°C.) on Smoke Index (Air Supply—4 Cubic Feet per Minute)

Time (seconds)	Galvanometer deflections (millimeters)										
	1	2	3	4	5	6	7	8	9	10	11
0	262	236	257	223	233	211	247	236	231	239	204
5	261	234	253	222	232	209	242	232	229	235	203
10	259	231	251	221	231	206	240	195	221	226	202
15	257	224	247	217	230	194	222	130	212	213	196
20	252	209	245	160	229	156	192	129	204	171	183
25	241	182	235	90	226	105	150	140	180	130	153
30	196	145	211	72	213	59	105	120	161	90	85
35	134	106	171	112	186	31	65	84	110	62	46
40	127	76	122	94	159	20	47	51	80	47	21
45	90	51	95	70	117	18	30	35	57	42	15
50	36	31	62	59	94	12	28	31	47	38	21
55	33	22	49	49	81	12	19	24	36	32	14
60	38	15	31	52	54	37	11	13	45	32	28
65	29	12	21	39	42	38	13	12	37	32	59
70	22	10	14	26	41	42	17	24	18	40	69
75	13	17	14	29	31	56	17	23	29	55	55
80	16	33	16	19	35	61	30	47	74	68	80
85	13	35	45	28	29	81	42	69	94	72	110
90	25	50	26	45	27	110	61	81	107	89	125
95	27	57	33	39	21	146	90	90	98	107	186
100	28	77	54	39	46	185	131	114	99	113	197
105	42	99	76	60	40	204	153	126	115	147	193
110	39	114	58	55	24	......	167	147	128	190	......
115	59	144	95	82	24	......	182	154	135	209	......
120	64	184	155	104	41	......	187	164	195	......	......
125	89	210	217	123	63	......	204	210	218	......	......
130	103	216	235	154	62	......	236	219	......	......	......
135	122	......	......	143	89	......	......	......	......	......	......
140	130	......	......	162	104	......	......	......	......	......	......
145	145	......	......	161	135	......	......	......	......	......	......
150	172	......	......	204	210	......	......	......	......	......	......
155	219	......	......	......	218	......	......	......	......	......	......
160	233	......	......	......	216	......	......	......	......	......	......
165	234	......	......	......	......	......	......	......	......	......	......
170	240	......	......	......	......	......	......	......	......	......	......
175	238	......	......	......	......	......	......	......	......	......	......
Total	4488	3020	3288	3153	3783	2193	3128	2900	3160	2679	2445
Number readings	36	27	27	31	33	22	27	27	26	24	22
A	124.7	111.9	121.8	101.7	114.6	99.7	115.9	107.4	121.5	111.6	111.1
B	250.0	226.0	246.0	213.5	224.5	207.5	241.5	227.5	224.5	224.0	198.5
X	50.1	50.5	50.5	52.4	49.0	52.0	52.0	52.8	45.9	50.2	44.0
T	175	130	130	150	160	105	130	130	125	115	105
S	8768	6565	6565	7860	7840	5460	6760	6864	5738	5773	4620
W	1.30	1.06	1.08	1.27	1.24	.82	1.03	1.02	.96	.89	.74
I (smoke index)	6740	6190	6080	6190	6320	6660	6560	6730	5980	6490	6240

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 14.—Effect of Temperature (700°C.) on Smoke Index (Air Supply—4 Cubic Feet per Minute)

Time (seconds)	Galvanometer deflections (millimeters)									
	1	2	3	4	5	6	7	8	9	10
0	222	220	195	197	207	239	251	240	229	222
5	220	209	182	152	130	120	238	238	226	217
10	195	134	110	82	71	66	218	234	222	216
15	70	63	59	51	53	55	197	226	87	190
20	24	35	39	42	48	47	47	112	48	60
25	20	34	41	36	45	44	34	61	60	39
30	22	79	36	31	59	38	47	72	54	36
35	31	98	61	31	73	35	66	67	55	43
40	41	81	91	42	55	55	81	90	104	58
45	42	84	105	61	51	84	91	99	115	71
50	57	43	112	103	43	84	108	68	148	82
55	74	31	131	117	57	100	81	63	132	86
60	72	56	140	132	42	127	70	76	115	116
65	96	84	145	148	67	127	91	76	123	125
70	72	96	154	149	107	120	110	69	138	120
75	61	131	161	158	66	170	123	106	153	113
80	135	179	174	172	49	197	183	103	163	87
85	174	189	......	......	87	......	208	138	182	72
90	182	......	......	......	137	......	......	158	184	106
95	......	......	......	......	......	......	......	171	186	151
100	......	......	......	......	......	......	......	172	......	152
105	......	......	......	......	......	......	......	......	......	158
110	......	......	......	......	......	......	......	......	......	163
115	......	......	......	......	......	......	......	......	......	165
120	......	......	......	......	......	......	......	......	......	167
125	......	......	......	......	......	......	......	......	......	168
130	......	......	......	......	......	......	......	......	......	170
135	......	......	......	......	......	......	......	......	......	171
140	......	......	......	......	......	......	......	......	......	171
145	......	......	......	......	......	......	......	......	......	172
150	......	......	......	......	......	......	......	......	......	......
Total	1810	1846	1936	1704	1447	1708	2244	2639	2724	3867
Number readings	19	18	17	17	19	17	18	21	20	30
A	95.3	102.6	113.9	100.2	76.2	100.5	124.7	125.7	136.2	128.9
B	202.0	204.5	184.5	184.5	172.0	218.0	229.5	206.0	207.5	197.0
X	52.8	49.8	38.3	45.7	55.7	53.9	45.7	39.0	34.4	34.6
T	90	85	80	80	90	80	85	100	95	145
S	4752	4233	3064	3656	5013	4312	3885	3900	3268	5017
W	1.14	.87	.77	.70	1.01	.87	.83	.93	.75	.88
I (smoke index)	4170	4870	3980	5220	4960	4960	4680	4190	4360	5700

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.
T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

TABLE 15.—EFFECT OF TEMPERATURE (800°C.) ON SMOKE INDEX (AIR SUPPLY—4 CUBIC FEET PER MINUTE)

Time (seconds)	Galvanometer deflections (millimeters)									
	1	2	3	4	5	6	7	8	9	10
0......	195	214	200	201	194	197	192	180	184	187
5......	190	210	197	194	191	190	185	140	180	184
10......	160	120	121	165	170	174	120	75	145	133
15......	92	63	56	71	103	115	33	32	85	82
20......	50	26	43	40	81	75	31	27	49	26
25......	29	27	38	24	54	68	45	40	46	39
30......	46	48	67	51	49	60	74	41	59	34
35......	47	61	76	68	57	62	75	55	60	63
40......	56	42	86	47	43	71	64	67	71	69
45......	51	50	71	45	40	104	97	108	30	117
50......	64	59	99	75	20	87	69	119	47	90
55......	95	77	110	85	38	87	64	124	63	126
60......	88	88	109	100	77	116	120	135	48	147
65......	103	74	108	119	62	107	130	141	51	168
70......	97	94	145	132	75	132	121	144	67	....
75......	126	110	168	133	94	155	153	150	91	....
80......	149	125	174	135	110	157	166	152	135	....
85......	150	143	175	146	137	159	166	153	142	....
90......	....	149	176	161	....	....	168	....	142	....
95......	....	148	177	....	....	....	....	....	142	....
100......	....	147	....	....	....	....	....	....	143	....
105......	....	145	....	....	....	....	....	....	146	....
110......	....	142	....	....	....	....	....	....	....	....
115......	....	144	....	....	....	....	....	....	....	....
120......	....	145	....	....	....	....	....	....	....	....
125......	....	146	....	....	....	....	....	....	....	....
130......	....	149	....	....	....	....	....	....	....	....
135......	....	....	....	....	....	....	....	....	....	....
Total..	1788	2946	2396	2010	1595	2116	2073	1883	2126	1465
Number readings	18	27	20	19	18	18	19	18	22	14
A.....	99.3	109.1	119.8	105.8	88.6	117.6	109.1	104.6	96.6	104.6
B.....	172.5	181.5	188.5	181.0	165.5	178.0	180.0	166.5	165.0	177.5
X.....	42.4	39.9	36.4	41.5	46.5	33.9	39.4	37.2	41.5	41.1
T.....	85	130	95	90	85	85	90	85	105	65
S.....	3604	5187	3458	3735	3953	2882	3546	3162	4358	2672
W....	1.04	1.15	.92	1.03	.96	.74	.87	.93	.80	.75
I (smoke index)	3470	4510	3760	3630	4120	3890	4080	3400	5450	3560

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100$.
T = total time in seconds.
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

TABLE 16.—EFFECT OF TEMPERATURE (900°C.) ON SMOKE INDEX (AIR SUPPLY—4 CUBIC FEET PER MINUTE)

Time (seconds)	Galvanometer deflections (millimeters)									
	1	2	3	4	5	6	7	8	9	10
0......	195	205	205	213	211	202	210	200	201	200
5......	190	202	199	212	210	200	208	131	196	184
10......	115	160	145	195	135	145	193	35	165	150
15......	18	45	74	113	31	41	82	19	59	96
20......	18	22	36	12	14	19	12	48	31	69
25......	55	41	48	8	17	40	34	81	49	103
30......	71	31	56	37	36	66	70	117	71	82
35......	64	39	100	37	72	75	55	80	40	69
40......	55	42	92	42	122	85	101	71	25	102
45......	104	61	84	73	123	70	127	79	44	127
50......	88	7	91	30	134	13	134	105	75	141
55......	106	13	90	60	146	50	136	131	104	155
60......	127	35	130	126	152	101	148	153	116	167
65......	142	70	142	146	157	133	161	161	124	....
70......	140	95	153	152	157	139	169	....	129	....
75......	142	145	154	153	158	138	169	....	132	....
80......	147	147	155	....	158	139	169	....	133	....
85......	....	....	....	....	160	140	170	....	....	....
90......	....	....	....	....	....	....	171	....	....	....
95......	....	....	....	....	....	....	171	....	....	....
100......	....	....	....	....	....	....	172	....	....	....
105......	....	....	....	....	....	....	173	....	....	....
110......	....	....	....	....	....	....	....	....	....	....
Total..	1777	1360	1954	1609	2193	1796	3035	1411	1694	1645
Number readings	17	17	17	16	18	18	22	14	17	13
A.....	104.5	80.0	114.9	100.6	121.8	99.8	138.0	100.8	99.6	126.5
B.....	171.0	176.0	180.0	183.0	185.5	171.0	191.5	180.5	167.0	183.5
X.....	38.9	54.5	36.2	45.0	34.3	41.6	27.9	44.2	40.4	31.1
T.....	80	80	80	75	85	85	105	65	80	60
S.....	3112	4360	2896	3375	2916	3536	2930	2873	3232	1866
W....	1.02	1.17	1.04	.92	.91	.93	.75	.85	1.06	.75
I (smoke index)	3050	3730	2780	3670	3200	3800	3910	3380	3050	2490

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.

T = total time in seconds.
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 17.—Effect of Temperature (1000°C.) on Smoke Index (Air Supply—4 Cubic Feet per Minute)

Time (seconds)	Galvanometer deflections (millimeters)									
	1	2	3	4	5	6	7	8	9	10
0......	186	187	202	181	189	182	189	200	195	179
5......	182	183	197	178	187	175	180	188	190	171
10......	130	160	100	116	156	60	115	157	120	130
15......	133	25	49	33	21	10	36	61	30	13
20......	125	18	76	55	24	39	21	58	57	4
25......	87	52	142	91	106	69	35	25	70	20
30......	96	64	132	116	157	118	79	52	66	68
35......	136	1	95	141	167	114	111	88	91	108
40......	163	20	162	165	176	80	120	115	136	141
45......	179	71	161	168	177	61	139	156	157	144
50......	179	129	180	171	179	125	156	169	174	147
55......	181	153	189	188	....	155	163	....	178	151
60......	....	154	190	....	....	162	166	....	180	....
65......	....	156	....	....	....	....	....	....	....	....
70......	....	159	....	....	....	....	....	....	....	....
75......	....	161	....	....	....	....	....	....	....	....
80......	....	162	....	....	....	....	....	....	....	....
85......	....	....	....	....	....	....	....	....	....	....
Total..	1777	1855	1875	1603	1539	1350	1510	1269	1644	1276
Number readings	12	17	13	12	11	13	13	11	13	12
A.....	148.1	109.1	144.2	133.6	139.9	103.8	116.2	115.4	126.5	106.3
B.....	183.5	174.5	196.0	184.5	184.0	172.0	177.5	184.5	187.5	165.0
X.....	19.3	37.5	26.4	27.6	24.0	39.7	34.5	37.5	32.5	35.6
T.....	55	80	60	55	50	60	60	50	60	55
S.....	1062	3000	1584	1518	1200	2382	2070	1875	1950	1958
W....	.65	1.00	.78	.78	.84	1.07	.98	.90	.71	.85
I (smoke index)	1630	3000	2030	1950	1430	2230	2110	2080	2750	2300

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.
T = total time in seconds.
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.*

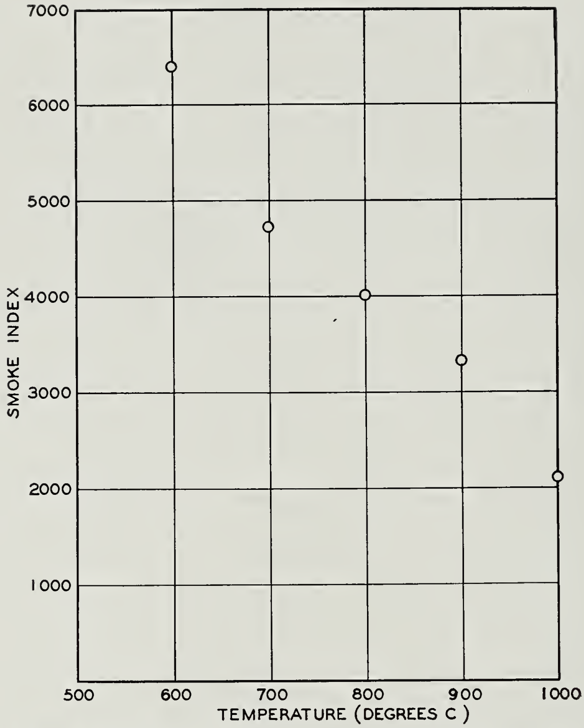

Fig. 14.—Effect of Temperature on Smoke Index.

Table 18.—Effect of Temperature on Smoke Index (Summary) (Air Supply—4 Cubic Feet per Minute)

(Data for Fig. 14)

Temperature °C.	Smoke indices				
	600°C.	700°C.	800°C.	900°C.	1000°C.
Test number—					
1	6740	4170	3470	3050	1630
2	6190	4870	4510	3730	3000
3	6080	3980	3760	2780	2030
4	6190	5220	3630	3670	1950
5	6320	4960	4120	3200	1430
6	6660	4960	3890	3800	2230
7	6560	4680	4080	3910	2110
8	6730	4190	3400	3380	2080
9	5980	4360	5450	3050	2750
10	6490	5700	3560	2490	2300
Average	6390	4710	3990	3310	2150

REPRODUCIBILITY OF SMOKE INDEX

A series of tests was made, using the preferred air supply of 4 cubic feet per minute and the preferred temperature of 600°C. in order to ascertain the degree of reproducibility of smoke index values. The individual results are shown in Table 19. It is seen that the per cent deviation from the average value varies from 0.9 to 6.3 per cent, with a mean deviation of 3.7 per cent.

The temperature of the furnace was maintained at 600±3°C., by means of a thermocouple and potentiometer. As noted previously, the temperature increases only about 3.0°C. due to the heat liberated by the coal sample.

The potential on the lamp fluctuates between 107 and 111 volts during the tests, but these fluctuations are rapid and therefore do not introduce an appreciable error.

The air supply remains constant to within a pressure difference of 2 mm. of mercury, which is equivalent to approximately 0.1 cubic foot per minute (see calibration curve for manometer, Fig. 8) for the rate of air flow used, namely 4 cubic feet per minute.

Also, there are additional errors due to temperature changes in the photoelectric cell, and of course no block of coal can provide two identical samples. But all these various errors are not cumulative and, therefore, the method has a maximum error of 6.3 per cent and an average error of 3.7 per cent for similar samples of coal.

Table 19.—Reproducibility of Smoke Indices (Air Supply—4 Cubic Feet per Minute)

Test number	Smoke index	Deviation from average	Per cent deviation from average
1	6740	+360	5.6
2	6190	—190	3.0
3	6080	—300	4.7
4	6190	—190	3.0
5	6320	−60	0.9
6	6660	+280	4.4
7	6560	+180	2.8
8	6730	+350	5.5
9	5980	—400	6.3
10	6490	+110	1.7
11	6240	—140	2.2
Average	6380	233	3.7

CHAPTER VI—APPLICATION OF SMOKE INDEX METHOD

The smoke index method was first developed as a means for comparing the amounts of smoke given off by impacted briquets (made without binder) and the natural coals from which the briquets were made. It has also been used in this laboratory to determine the relative smokiness of smokeless fuel briquets as compared with ordinary briquets and natural coals. Smokeless fuel briquets, as herein referred to, are briquets impacted without binder from partially volatilized bituminous coal. In this last connection, the smoke index method served admirably the purpose of indicating just when a smokeless fuel condition was reached, thus determining exactly how much volatile matter must be driven off before a smokeless fuel briquet is obtained. The smoke index method may be extended to compare the smokiness of two different types of briquets, of briquets and natural coals of all kinds, and of two different natural coals; in short, it can be used to compare the relative smokiness of any two kinds of fuel within limits. When the method is used merely for comparative purposes, the apparatus need only give comparative results since absolute values are not needed, the tests all being made in the same apparatus held under constant operating conditions, and the relative smokiness of the fuels thus being accurately determined.

However, the method need not be limited to one of comparison only. Such a method can be made suitable for determining the inherent smokiness of any fuel under certain controlled conditions and it was with this idea in mind that the series of smoke index tests on naphthalene was made. A standard material should be used for calibrating the apparatus if results are to be reproduced in other laboratories. When this is done there is no reason why the same smoke index of a fuel cannot be obtained in various laboratories.

With sets of apparatus giving reproducible results and with representative samples, the smoke index method affords the means of determining the smokiness of any fuel in terms of the amount of smoke given off per unit weight.

The smoke index method will give the relative smokiness of two different types of coal without actually burning large quantities of the two coals.

The use of the smoke index method is illustrated by the following detailed results on the smoke index of naturally occurring coals of various volatile matter content and that of Illinois coal fines processed to various volatile matter contents by the method herein described.

SMOKE INDEX OF THE NATURAL COALS

Will County coal.—The experimental data and computations on the smoke index of eight portions of a sample of Will County coal in the first series of tests are given in Table 20. The average analysis of this coal (Table 1, Part I of report) shows a content of 43.5 per cent volatile matter and 9.1 per cent moisture (partly air dried).

The smoke index values, computed as described above, ranged from 4330 to 6260, and averaged 5350. This variation in smoke index values appears to be due to the banded character of bituminous coals, banded ingredients varying in their respective smoke content. On account of the heterogeneous character of coal, therefore, the smoke index value is obtained by averaging the values from several determinations.

Approximately three months later a second series of six smoke index tests (Table 21) were made on remaining portions of the same sample of coal to determine the effect of storage. As shown by the table, the values ran lower, ranging from 3630 to 4730, and averaging 4220. These lower values may reflect a possible loss of moisture and volatile matter during storage.

Table 20.—Smoke Index Data on Will County (B) Coal (Series No. 1)

(Average Analysis of this Coal bed: Volatile Matter 43.5 Per Cent; Moisture 9.1 Per Cent Partly Air Dried)

Time (seconds)	Test Samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (a) (mm.)							
0	194	243	227	250	235	237	210	222
5	195	242	227	248	233	235	207	224
10	198	241	227	248	230	237	205	222
15	191	240	227	250	228	233	205	223
20	194	238	227	241	225	232	201	222
25	193	237	204	246	224	226	197	219
30	187	235	180	230	219	213	186	218
35	184	230	160	220	206	186	179	214
40	176	224	140	200	200	180	155	205
45	165	216	120	200	180	155	140	183
50	145	207	100	150	138	147	120	171
55	115	199	80	130	110	136	105	175
60	116	190	60	90	0	100	98	164
65	119	175	47	66	20	92	77	128
70	100	160	43	52	17	79	61	111
75	85	142	36	36	30	75	58	110
80	76	124	40	30	60	0	65	110
85	53	120	66	30	60	57	60	80
90	50	116	36	24	67	50	73	74
95	47	111	34	30	77	50	82	57

Table 20.—Concluded

Time (seconds)	Test Samples 1	2	3	4	5	6	7	8	
	Galvanometer deflections (*a*) (mm.)								
100	45	105	44	35	60	66	57	54	
105	64	98	44	16	90	69	50	90	
110	31	90	62	46	80	65	61	30	
115	79	85	69	21	80	67	60	30	
120	43	80	65	90	100	75	61	47	
125	35	85	93	45	90	78	35	60	
130	44	90	110	150	120	82	28	110	
135	57	78	112	100	130	85	36	105	
140	70	65	180	100	200	105	60	150	
145	80	80	200	150	190	150	105	205	
150	63	95	190	160	190	212	160	194	
155	74	101	196	250	200	188	180	199	
160	100	107	200	230	195	200	205	....	
165	130	114	200	235	195	195	184	....	
170	180	220	....	235	....	196	192	....	
175	185	220	....	....	....	....	....	....	
180	176	220	....	....	....	....	....	....	
Total	4239	5823	4246	4834	4679	4753	4158	4606	
Number readings	37	37	34	35	34	35	35	32	
A	114.6	157.4	124.9	138.1	137.6	135.8	118.8	143.9	
B	185.0	231.5	213.5	242.5	215.0	216.5	201.0	210.5	
X	38.1	32.0	41.4	43.1	36.0	37.3	40.9	31.6	
T	180	180	165	170	165	170	170	155	
S	6858	5760	6831	7327	5940	6341	6953	4898	Average
W	1.26	1.20	1.22	1.17	1.17	1.22	1.15	1.13	smoke
I (smoke index)	5440	4800	5600	6260	5080	5200	6050	4330	index 5350

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.

T = total time (sec.)
S = total smoke = X × T.
W = weight of sample (grams).
I = smoke index = S/W.
a—The highest value of the galvanometer deflection represents no smoke and the lowest value, maximum smoke. See Part II of the Report for complete description of the smoke index method.

TABLE 21.—SMOKE INDEX DATA ON WILL COUNTY (B) COAL (SERIES NO. 2)
(Same Coal as Series No. 1 after 3 Months Storage)

Time (seconds)	Test samples 1	2	3	4	5	6	
	Galvanometer deflections						
0	213	203	204	202	212	204	
5	204	199	201	199	208	195	
10	197	193	191	194	202	175	
15	179	186	195	192	160	124	
20	169	159	166	180	115	103	
25	126	117	140	136	76	131	
30	119	112	126	160	80	65	
35	99	112	105	123	91	95	
40	79	117	79	159	80	87	
45	64	132	69	96	83	102	
50	46	70	86	66	69	107	
55	46	92	40	100	60	111	
60	41	63	69	70	77	124	
65	43	85	71	105	55	127	
70	26	83	58	52	72	111	
75	23	73	88	90	96	128	
80	23	72	111	72	76	122	
85	33	87	105	85	92	94	
90	130	72	123	115	82	93	
95	59	43	128	85	74	86	
100	109	85	102	125	115	132	
105	107	83	116	122	79	134	
110	139	78	106	119	148	138	
115	132	78	110	127	141	116	
120	122	92	122	115	169	138	
125	120	128	131	106	189	145	
130	143	128	107	134	....	165	
135	151	122	149	132	....	174	
140	161	115	172	136	....	186	
145	175	137	182	152	....	....	
150	196	180	179	191	....	....	
155	....	....	186	....	....	....	
Total	3474	3496	4017	3940	2901	3712	
Number readings	31	31	32	31	26	29	
A	112.1	112.8	125.5	127.1	111.6	128.0	
B	204.5	191.5	195.0	196.5	200.5	195.0	
X	45.2	41.1	35.6	35.3	44.3	34.4	
T	150	150	155	150	125	140	Average
S	6780	6165	5518	5295	5538	4816	smoke
W	1.47	1.35	1.38	1.46	1.17	1.28	index
I (smoke index)	4610	4570	4000	3630	4730	3760	4220

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.
T = total time (sec.)
S = total smoke = X × T.
W = weight of sample (grams).
I = smoke index = S/W.

Washington County coal.—Table 22 gives the experimental data on Washington County coal. The smoke index values for nine tests ranged from 3890 to 5050 and averaged 4380. The character of this coal is approximately that indicated by the analysis of Washington County coal in Table 1 (Part I, p. 18). It contained 41.5 per cent volatile matter and 8.5 per cent moisture.

Table 22.—Smoke Index Data on Washington County Coal

(Analysis of Sample: Volatile Matter 41.5 Per Cent; Moisture 8.5 Per Cent Partly Air Dried)

Time (seconds)	Test samples								
	1	2	3	4	5	6	7	8	9
	Galvanometer deflections (mm.)								
0......	220	226	210	196	223	184	200	218	188
5......	220	222	210	195	223	182	200	219	190
10......	218	223	210	198	223	185	198	219	188
15......	218	222	210	194	222	180	200	216	186
20......	215	218	208	155	220	182	197	214	184
25......	212	220	209	136	218	182	190	189	172
30......	195	213	190	120	212	168	186	185	125
35......	180	184	177	100	200	151	156	142	91
40......	171	181	180	65	190	146	125	122	110
45......	152	146	155	65	173	140	103	75	74
50......	139	142	140	20	169	118	96	79	64
55......	133	146	104	50	156	105	109	60	30
60......	127	119	66	56	117	95	80	51	4
65......	99	119	79	45	86	45	1	59	29
70......	90	101	35	82	94	30	30	56	25
75......	76	90	10	84	69	41	30	83	33
80......	95	75	17	52	101	46	59	9	33
85......	38	70	19	68	0	56	56	37	47
90......	38	65	25	70	50	62	54	39	35
95......	89	70	32	76	29	47	27	42	45
100......	47	30	32	70	57	67	90	29	35
105......	55	55	60	71	100	46	95	55	60
110......	123	51	54	81	41	79	81	56	50
115......	102	71	63	70	68	90	96	67	50
120......	82	96	85	54	70	99	90	70	80
125......	100	109	74	101	60	107	80	77	54
130......	115	120	99	119	95	124	101	77	87
135......	137	119	144	172	101	162	110	113	117
140......	204	131	150	155	105	144	115	124	159
145......	184	139	150	169	190	153	130	184	140
150......	190	154	151	173	184	150	145	165	146
155......	195	170	156	....	177	148	173	173	146
160......	....	207	158	....	184	152	159	172	150
165......	....	192	163	....	184	150	163	174	161
170......	....	199	....	....	190	150	160	175	153
175......	....	194	....	....	....	158	161	....	157
180......	....	190	....	....	....	....	163	....	....
185......	....	194	....	....	....	....	160	....	....

TABLE 22.—Concluded

Time (seconds)	Test samples									
	1	2	3	4	5	6	7	8	9	
	Galvanometer deflctions (mm.)									
190	......	196	......	......	......	......	160	......	......	
195	......	......	......	......	......	......	160	......	......	
200	......	......	......	......	......	......	173	......	......	
Total	4459	5669	4025	3262	4781	4324	5062	4025	3598	
Number readings	32	39	34	31	35	36	41	35	36	
A	139.3	145.4	118.4	105.2	136.6	120.1	123.5	115.0	99.9	
B	207.5	211.0	186.5	184.5	206.5	171.0	186.5	196.5	172.5	
X	32.9	31.1	36.5	43.0	33.8	29.8	33.8	41.5	42.1	
T	155	190	165	150	170	175	200	170	175	
S	5100	5909	6023	6450	5746	5215	6760	7055	7368	
W	1.31	1.38	1.45	1.55	1.34	1.31	1.40	1.47	1.46	Average smoke index
I (smoke index)	3890	4280	4150	4160	4290	3980	4810	4800	5050	4380

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.

T = total time (seconds).
S = total smoke = X × T.
W = weight of sample (grams).
I = smoke index = S/W.

Franklin County coal.—Table 23 gives the experimental data on Franklin County coal. The smoke index values for seven tests ranged from 3200 to 3810 and averaged 3650. This coal is similar to that represented by the analysis of Franklin County coal in Table 1 (Part I of report). It contained approximately 33.8 per cent volatile matter and 8.7 per cent moisture.

Table 23.—Smoke Index Data on Franklin County (B) Coal
(Analysis of Sample: Volatile Matter 33.8 Per cent; Moisture 8.7 Per Cent)

Time (seconds)	Test samples 1	2	3	4	5	6	7	
	Galvanometer deflections							
0	216	205	190	179	180	230	260	
5	213	202	188	178	178	228	250	
10	210	195	187	176	172	225	251	
15	208	194	188	176	171	215	253	
20	204	190	185	174	158	210	240	
25	195	175	180	163	152	197	225	
30	178	160	174	145	129	193	210	
35	160	142	160	130	119	179	205	
40	137	142	145	110	112	169	180	
45	125	115	135	104	101	156	165	
50	107	102	123	91	76	174	142	
55	90	90	119	81	73	50	120	
60	74	89	115	84	59	36	110	
65	70	100	10	35	90	58	30	
70	55	17	55	40	50	64	70	
75	50	47	40	40	35	76	55	
80	50	42	80	50	38	58	80	
85	55	55	65	45	54	64	105	
90	90	55	80	52	57	77	125	
95	60	85	89	49	59	115	120	
100	80	110	90	83	47	63	105	
105	120	130	92	104	57	74	140	
110	90	105	103	99	78	123	135	
115	150	130	108	114	86	128	165	
120	125	140	136	104	79	143	20	
125	120	190	128	117	106	165	105	
130	170	175	130	133	107	194	130	
135	177	180	130	142	127	195	142	
140	195	....	....	162	135	197	170	
145	....	....	170	157	135	197	230	
150	....	....	175	159	141	199	....	
155	....	....	....	....	137	....	....	
Total	3774	3562	3770	3476	3298	4452	4538	
Number readings	29	28	30	31	32	31	30	
A	130.1	127.2	125.7	112.1	103.1	143.6	151.3	
B	205.5	192.5	182.5	169.0	158.5	214.5	245.0	
X	36.7	33.9	31.1	33.7	35.0	33.1	38.2	
T	140	135	150	150	155	150	145	Average
S	5138	4577	4665	5055	5425	4965	5539	smoke
W	1.35	1.25	1.30	1.37	1.42	1.55	1.46	index
I (smoke index)	3810	3660	3590	3690	3820	3200	3790	3650

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100$.
T = total time (seconds).
S = total smoke = X × T.
W = weight of sample (grams).
I = smoke index = S/W.

West Virginia coals.—Table 24 gives the experimental data on West Virginia (A) and West Virginia (B), Beckley bed, and West Virginia (C), Jewell bed. For West Virginia (A) the smoke index values for four tests ranged from 1540 to 2070 and averaged 1770; for West Virginia (B) the values for four tests ranged from 1580 to 2200 and averaged 1820; and for West Virginia (C) the values for three tests ranged from 2550 to 2970 and averaged 2720. According to Black's Directory, Fourth Edition, 1935, the coals contain 16.2, 17.7 and 22.5 per cent volatile matter, and 0.7, 0.0, and 1.4 per cent moisture respectively.

Table 24.—Smoke Index of West Virginia Coals

Time (seconds)	Sample A (Beckley Co.) (Volatile matter 16.2 per cent) "as received"				Sample B (Raleigh Co.) (Volatile matter 17.7 per cent) "as received"				Sample C (Jewell Co.) (Volatile matter 22.5 per cent) "as received"		
	Test samples										
	1	2	1	2	1	2	1	2	1	2	3
	Galvanometer deflections (mm.)										
0	181	184	173	188	187	184	193	186	185	187	188
5	181	184	173	188	187	184	192	186	184	187	188
10	181	184	173	188	188	184	192	186	184	185	187
15	181	184	173	187	188	183	193	186	183	186	186
20	181	184	173	188	187	183	193	185	179	185	187
25	181	183	172	188	187	184	193	186	172	185	184
30	181	181	171	187	186	183	192	186	162	182	177
35	179	179	167	187	186	182	190	184	148	176	173
40	179	175	162	185	184	182	189	183	138	166	166
45	178	169	153	182	180	181	186	180	133	159	166
50	172	162	154	176	173	179	183	172	119	153	163
55	166	161	151	166	171	176	178	163	113	141	148
60	159	152	142	156	165	172	171	138	106	141	149
65	150	149	134	143	153	168	161	132	99	124	92
70	137	156	123	139	141	161	156	138	93	109	83
75	134	131	116	134	129	156	148	164	91	67	83
80	134	123	132	128	116	146	141	159	91	70	84
85	132	139	130	123	107	139	132	172	103	70	84
90	116	136	130	116	108	145	116	177	76	69	87
95	137	133	132	115	139	103	103	154	79	76	98
100	142	114	142	106	126	98	97	134	82	78	109
105	146	98	147	111	118	106	120	121	77	84	123
110	151	76	147	141	115	115	112	132	81	87	131
115	149	101	155	143	98	102	116	161	86	93	136
120	105	109	163	156	105	98	129	181	92	99	143
125	83	117	143	168	117	130	148	184	102	103	147
130	104	114	96	175	123	120	160	......	108	113	154
135	108	126	110	177	129	125	175	......	118	119	161
140	122	132	118	180	133	123	182	......	126	122	166

TABLE 24.—Concluded

Time (seconds)	Sample A (Beckley Co.) (Volatile matter 16.2 per cent) "as received"				Sample B (Raleigh Co.) (Volatile matter 17.7 per cent) "as received"				Sample C (Jewell Co.) (Volatile matter 22.5 per cent) "as received"		
	Test samples										
	1	2	1	2	1	2	1	2	1	2	3
	Galvanometer deflections (mm.)										
145	131	147	132	181	142	130	186	......	132	131	171
150	134	172	113	183	151	137	......	......	138	135	177
155	136	174	131	......	162	92	......	......	143	142	178
160	139	......	152	......	181	105	......	......	145	148	179
165	141	......	161	......	184	130	......	......	150	159	......
170	143	......	169	......	......	151	......	......	153	165	......
175	153	......	170	......	......	174	......	......	164	170	......
180	167	......	171	......	......	......	......	......	166	174	......
185	168	......	......	......	......	......	......	......	167	......	......
190	......	......	......	......	......	......	......	......	169	......	......
Total	5662	4729	5454	4985	5146	5311	4827	4330	5037	4940	4848
Number readings	38	32	37	31	34	36	30	26	39	37	33
A	149.0	147.8	147.4	160.8	151.4	147.5	160.9	166.5	129.2	133.5	146.9
B	174.5	179.0	172.0	185.5	185.5	179.0	189.5	185.0	177.0	180.5	183.5
X	14.6	17.4	14.3	13.3	18.4	17.6	15.1	10.0	27.0	26.0	19.9
T	185	155	180	150	165	175	145	125	190	180	160
S	2701	2697	2574	1995	3036	3080	2190	1250	5130	4680	3184
W	1.48	1.30	1.67	1.21	1.38	1.60	1.39	0.79	1.73	1.78	1.25
I (smoke index)	1830	2070	1540	1650	2200	1930	1580	1580	2970	2630	2550
	Average=1770				Average=1820				Average=2720		

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100$.

T = total time (seconds).
S = total smoke = X × T.
W = weight of sample (grams).
I = smoke index = S/W.

RELATIONSHIP BETWEEN SMOKE CONTENT AND VOLATILE MATTER OF NATURAL COALS

The foregoing results are summarized in Table 25 and also in a graph (Fig. 15) in which the average smoke index is plotted against the percentage of volatile matter, an inspection of which indicates an approximation of a straight-line relationship for the seven coals tested.

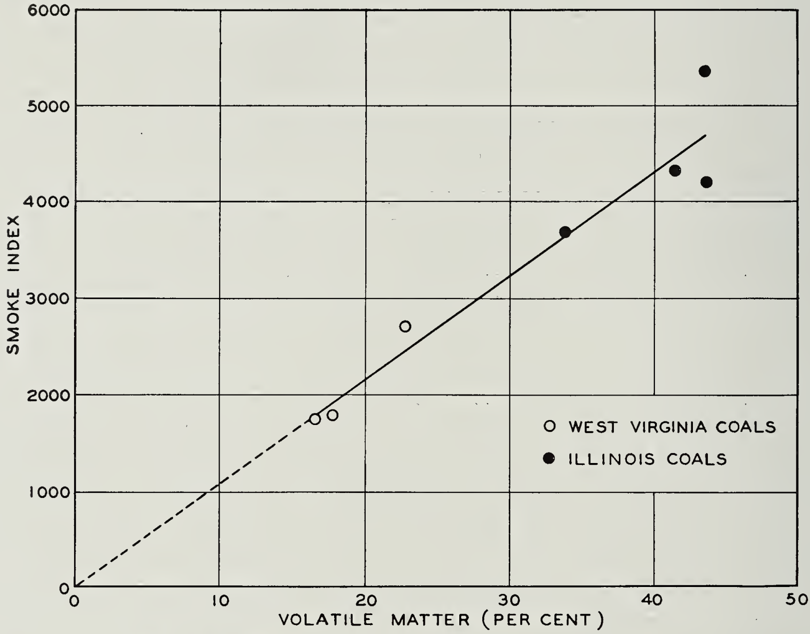

Fig. 15.—Effect of the Amount of Naturally Occurring Volatile Matter on the Smoke Index of Coal.

Table 25.—Effect of Amount of Naturally Occurring Volatile Matter on Smoke Index of Coal

(Data for Fig. 15)

Location	Bed	Moisture (*a*) (per cent)	Volatile matter (*a*) (per cent)	Average smoke index
Will County (Series No. 1)	2	9.1	43.5	5350
Will County (Series No. 2)	2	(*b*)	(*b*)	4220
Washington County	6	8.5	41.5	4380
Franklin County	6	8.7	33.8	3650
West Virginia (A)	Beckley	0.7	16.2	1770
West Virginia (B)	Beckley	0.0	17.7	1820
West Virginia (C)	Jewell	1.4	22.5	2720

(*a*) As received basis.
(*b*) Same coal as used in Will County Series No. 1 after three months storage.

CALCULATION OF VOLATILE MATTER IN PARTIALLY VOLATILIZED COALS

Analyses of coal heated from 275°C. to about 500°C. indicate that losses in weight are due, as would be expected, to loss in volatile matter (Table 26). In the present studies this loss in weight is therefore used directly as a means of determining the volatile matter content of the partially volatilized coal according to the following formula:

$$VM_X = \frac{VM_D - L_D}{100 - L_D}$$

where VM_D is the per cent volatile matter in the raw coal (dry basis) and L_D is the per cent loss in weight above 275°C. or on the dry basis.

This calculation may be illustrated by an example taken from values in Table 26. In order to calculate the per cent volatile matter in sample C-737 from the volatile matter in sample C-738, the above equation becomes as follows:

$$VM_D = \frac{43.9 - 13.4}{100 - 13.4} = 35.3$$

Removal of volatile matter will of course produce a corresponding increase in fixed carbon and ash according to the formula

$$\frac{\text{Fixed carbon (or ash)}_{T = L}}{100 - L_D} = \text{Fixed carbon (or ash)}_{T = H}$$

where T = L is the per cent at a certain temperature and T = H is that at a higher temperature.

The volatile matter lost probably will include some sulfur, hence the amount of sulfur present in the coal at increasingly higher temperatures above 275°C., can be known only by analysis. The data in Table 26 indicate that for these samples more than 25 per cent of the sulfur is volatilized between 275°C. and 530°C.

TABLE 26.—ANALYSES OF BRIQUETS VOLATILIZED TO VARIOUS STAGES OF VOLATILIZATION (*a*)

Analysis No. (*b*)	County	Bed	Oven temperature (*c*) (°C.)	Weight loss (per cent)	Volatile matter (per cent)		Ash (per cent)		Fixed carbon (per cent)		Total sulfur (per cent)		B. t. u.
					Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	
C-738	Will	2	275	0.0	43.9	43.9	5.3	5.3	50.8	50.8	3.4	3.4	13299
C-737	Will	2	500	13.4	35.5	35.3	6.0	6.1	58.6	58.6	3.1	3.9	13297
C-736	Will	2	515	15.9	32.7	33.3	6.9	6.3	60.4	60.4	3.1	4.0	13250
C-735	Will	2	530	19.0	31.0	30.7	6.3	6.5	62.6	62.8	3.3	4.2	13288
C-740	Franklin	6	275	0.0	35.9	35.9	7.1	7.1	57.0	57.0	1.1	1.1	13246
C-884	Franklin	6	450	5.6	32.0	32.1	7.6	7.5	60.4	60.4	1.0	1.2	13132
C-885	Franklin	6	475	8.8	30.2	29.7	7.4	7.8	62.4	62.5	1.0	1.2	13188
C-886	Franklin	6	500	12.8	26.3	26.5	7.8	8.1	65.4	65.4	1.0	1.3	13098
C-887	Franklin	6	525	15.7	24.4	23.9	8.1	8.4	67.5	67.7	0.9	1.3	12981

(*a*) Analyses made in 1934, all values on moisture-free basis.
(*b*) C-738, 737, 736, and 735 are portions of one Will County sample; C-740, 884, 885, 886, and 887 are likewise portions of one Franklin County sample.
(*c*) Volatilization period of 10 minutes.

SMOKE INDEX OF BRIQUETS MADE BY IMPACT FROM PARTIALLY VOLATILIZED COALS

The samples of coal from Will and Franklin counties were volatilized to various degrees, and briquets without artificial binder were made by the impact process in order to determine the smoke indices of the partially volatilized coal.

The minus 4-mesh coal was first heated for 10 minutes at a temperature of 275°C., the loss of weight being assigned to moisture loss; subsequent losses in weight at higher temperatures were assigned to volatile matter, and from such loss the volatile matter remaining in the coal was calculated, using the formula given above.

Will County briquets.—Separate portions of the sample of Will County coal were preheated for 10 minutes, each at a different temperature. These products were then briquetted and from four to eight duplicate smoke index tests were made on 1-cm. cubes cut from the briquets.

The data are shown in tabular form as follows: Table 27 for briquetted coal preheated at 250°C. (coal temperature), retaining its original 43.9 per cent volatile matter; Table 28 for the product partially volatilized at 477°C. and containing 39.3 per cent volatile matter; Table 29 for the product partially volatilized at 485°C. and containing 35.8 per cent volatile matter; Table 30, for the product partially volatilized at 505°C. and containing 31.9 per cent volatile matter; Table 31, for the product partially volatilized at 515°C. and containing 24.3 per cent volatile matter; and Table 32, for the product partially volatilized at 535°C. and containing 16.4 per cent volatile matter.

The data are averaged and summarized in Table 6 (Part I of report), including the individual smoke indices with the exception of those of the sample prevolatilized at 477°C. shown in Table 28. Apparently volatilization was not uniform throughout this sample, possibly due to the greater volatilization of the smaller grains of coal.

In figure 5 (Part I of report) the smoke index is plotted against the volatile matter content of the partially prevolatilized briquets. This curve indicates a linear relationship for Will County coal for briquets volatilized at temperatures of 250°, 477°, 485°, and 505°C. Those volatilized at temperatures of 515° and 535°C. possess a smoke index of less than 150.

Table 27.—Smoke Index of Nonvolatilized Will County Briquet Containing 43.9 Per Cent Volatile Matter at Temperature of 250°C. for 10 Minutes

Time (seconds)	Test samples						
	1	2	3	4	5	6	7
	Galvanometer deflections (mm.)						
0	201	219	203	230	210	212	204
5	199	214	195	229	206	200	202
10	191	216	186	222	185	181	202
15	171	215	183	150	144	143	200
20	136	206	130	98	125	125	199
25	112	186	84	115	104	110	179
30	90	164	79	92	106	134	147
35	91	151	63	86	64	71	113
40	89	90	80	103	56	97	98
45	86	66	45	80	76	102	92
50	78	90	71	76	70	100	89
55	79	71	71	103	79	99	82
60	90	81	79	82	91	110	95
65	100	82	85	73	95	107	110
70	111	92	94	103	96	98	89
75	101	92	100	98	99	104	96
80	115	96	95	103	100	106	120
85	100	101	85	81	115	96	133
90	100	84	100	86	113	104	136
95	100	85	102	105	130	114	147
100	100	84	112	110	91	114	142
105	105	93	115	129	109	119	153
110	115	99	131	140	105	150	172
115	124	86	138	176	163	157	181
120	139	104	86	170	....	170	198
125	155	121	110	177	182	183	....
130	160	140	143	191	....	192	....
135	175	161	155	....	....	189	....
140	....	169	174	....	....	188	....
145	....	187	178	....	....	191	....
150	....	188	173	....	....	193	....
155	....	195	174	....	....	....	....
160	....	....	177	....	....	....	....
165	....	....	178	....	....	....	....
170	....	....	179	....	....	....	....
Total	3413	4228	4353	3408	2914	4259	3579
Number of readings	28	32	35	27	25	31	25
A	121.9	132.1	124.4	126.2	116.6	137.4	143.2
B	188.0	207.0	191.0	210.5	196.0	202.5	201.0
X	35.2	36.2	34.9	40.0	40.5	32.1	28.8
T	135	155	170	130	125	150	120
S	4752	5611	5933	5200	5063	4815	3456
W	1.47	1.53	1.45	1.37	1.30	1.39	1.03
I (smoke index)	3230	3670	4090	3800	3890	3460	3360

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.
T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 28.—Smoke Index of Will County Briquets Volatilized to 39.3 Per Cent Volatile Matter at Temperature of 477°C. for 10 Minutes

Time (seconds)	Test samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (mm.)							
0	236	224	224	214	210	215	206	212
5	233	221	222	212	209	209	202	208
10	224	221	218	208	208	208	195	210
15	199	218	174	180	207	202	174	206
20	152	212	159	134	204	178	169	190
25	151	188	141	100	194	139	157	169
30	119	175	115	112	191	129	149	162
35	124	150	130	81	174	105	140	139
40	122	128	111	108	165	96	143	145
45	125	123	123	95	155	129	129	122
50	123	122	122	98	152	96	148	134
55	126	118	130	99	130	115	135	139
60	115	110	129	93	106	115	146	134
65	121	145	144	88	113	113	126	151
70	110	203	129	107	109	119	137	139
75	109	164	124	113	117	116	133	126
80	126	166	145	101	113	122	141	135
85	129	170	161	97	125	134	148	132
90	133	160	105	106	130	132	151	139
95	130	154	181	109	127	118	163	135
100	123	173	159	100	143	113	173	143
105	132	167	165	110	152	142	177	167
110	174	198	193	125	168	149	198	173
115	195	205	188	155	182	159	202	185
120	218	218	205	158	203	179	....	187
125	212	216	207	175	....	191	....	195
130	213	222	206	194	....	198	....	201
135	215	....	207	195	....	....	....	203
140	221	....	207	196	....	....	....	202
145	216	....	209	....	....	....	....	204
150	218	....	210	....	....	....	....	....
155	220	....	....	....	....	....	....	....
160	222	....	....	....	....	....	....	....
Total	5487	4771	5143	3863	3987	3921	3842	4987
Number readings	33	27	31	29	25	27	24	30
A	166.3	176.7	165.9	133.2	159.5	145.2	160.1	166.2
B	229.0	223.0	217.0	205.0	206.5	206.5	204.0	208.0
X	27.4	20.8	23.5	35.0	22.8	29.7	21.5	20.1
T	160	130	150	140	120	130	115	145
S	4384	2704	3525	4900	2736	3861	2473	2915
W	1.24	1.44	1.05	1.44	1.35	1.27	1.43	1.53
I (smoke index)	3540	1880	3360	3400	2030	3040	1730	1910

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$.
T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 29.—Smoke Index of Eight 1-cm. Cubes Cut from a Will County Briquet Volatilized to 35.8 Per Cent Volatile Matter at Temperature of 485°C. for 10 Minutes.

Time (seconds)	Test samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (mm.)							
0	222	221	217	215	213	207	211	206
5	217	219	216	208	209	....	204	203
10	202	219	206	214	203	205	202	203
15	189	215	196	208	200	196	191	197
20	178	199	189	201	183	191	184	188
25	157	180	172	181	167	174	171	173
30	156	165	159	165	156	160	156	167
35	151	142	154	151	135	151	145	156
40	140	141	156	143	142	136	121	137
45	155	143	146	151	131	136	132	143
50	141	157	144	141	139	128	118	134
55	160	156	147	137	123	130	127	123
60	147	178	150	126	130	120	125	136
65	167	166	161	148	117	123	126	124
70	164	166	158	135	127	137	113	126
75	162	191	156	143	140	132	143	139
80	168	177	171	148	130	138	135	132
85	170	190	162	147	147	145	146	143
90	174	184	164	149	154	148	151	155
95	186	194	174	166	170	151	163	166
100	187	196	179	155	176	162	171	177
105	203	206	195	172	192	168	166	195
110	214	213	195	180	202	183	173	196
115	217	217	199	184	205	191	183	200
120	221	....	209	201	208	198	197	....
125	....	....	217	210	....	207	206	203
Total	4448	4435	4592	4379	4099	4017	4160	4122
Number readings	25	24	26	26	25	25	26	25
A	177.9	184.8	176.6	168.4	164.0	160.7	160.0	164.9
B	221.5	219.0	217.0	212.5	210.5	207.0	208.5	204.5
X	19.7	15.6	18.6	20.8	22.1	22.4	23.3	19.4
T	120	115	125	125	125	125	125	125
S	2364	1794	2325	2600	2652	2800	2913	2425
W	1.44	1.13	1.58	1.38	1.34	1.54	1.52	1.33
I (smoke index)	1640	1590	1470	1880	1980	1820	1920	1820

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100.$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 30.—Smoke Index of Will County Briquets Volatilized to 31.9 Per Cent Volatile Matter at Temperature of 505°C. for 10 Minutes

Time (seconds)	Test samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (mm.)							
0	231	231	237	241	241	255	240	237
5	229	226	234	234	240	249	239	233
10	223	222	235	239	233	250	236	231
15	224	213	233	236	234	246	233	236
20	220	205	230	233	226	249	233	232
25	217	194	226	231	229	237	233	232
30	211	186	221	229	221	242	226	224
35	210	187	216	229	222	234	227	223
40	207	177	218	225	219	231	225	223
45	215	183	217	225	213	226	222	221
50	206	181	215	222	220	240	227	219
55	224	184	210	226	209	233	227	214
60	216	190	213	218	210	226	218	216
65	217	187	210	230	204	232	217	212
70	218	197	206	227	208	224	215	216
75	221	197	212	232	205	223	218	213
80	222	224	210	233	211	219	213	218
85	225	225	209	....	202	223	226	213
90	228	228	217	239	179	231	232	213
95	229	....	223	242	184	233	235	217
100	....	....	231	....	189	249	239	225
105	....	....	233	....	194	252	....	233
110	....	....	234	....	212	....	....	233
115	....	....	235	....	232	....	....	234
120	....	....	....	....	243	....	....	237
Total	4393	3837	5325	4391	5380	5204	4781	5605
Number readings	20	19	24	19	25	22	21	25
A	219.7	201.9	221.9	231.1	215.2	236.5	227.7	224.2
B	230.0	229.5	236.0	241.5	242.0	253.5	239.5	237.0
X	4.48	12.0	5.97	4.31	11.1	6.71	4.93	5.40
T	95	90	115	95	120	105	100	125
S	426	1080	687	409	1332	705	493	675
W	1.62	1.39	1.25	1.50	1.53	1.34	1.52	1.42
I (smoke index)	263	777	550	273	871	526	324	475

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 31.—Smoke Index of Will County Briquets Volatilized to 24.3 Per Cent Volatile Matter at Temperature of 515°C. for 10 Minutes

Time (seconds)	Test samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (mm.)							
0	227	224	230	229	230	238	233	232
5	225	221	226	227	229	235	230	228
10	223	221	224	226	229	235	227	229
15	216	221	227	225	223	234	228	226
20	216	219	227	227	220	234	227	205
25	214	216	226	229	217	236	227	208
30	215	213	221	227	213	236	224	213
35	215	217	221	227	206	236	227	215
40	213	219	223	227	207	234	227	221
45	215	219	220	226	213	230	229	224
50	220	219	221	227	218	234	226	234
55	196	220	220	221	225	233	229	229
60	218	223	226	227	225	230	233	229
65	209	226	226	218	....	238	229	233
70	217	....	225	222	....	....	234	....
75	219	....	224	218	228	....	....	....
80	226	....	230	221	....	....	....	....
85	220	....	....	220	....	....	....	....
90	228	....	....	225	....	....	....	....
Total	4132	3078	3817	4269	3083	3283	3430	3126
Number readings	19	14	17	19	14	14	15	14
A	217.5	219.9	224.5	224.7	220.2	234.5	228.7	223.3
B	227.5	225.0	230.0	227.0	229.0	238.0	233.5	232.5
X	4.39	2.27	2.39	1.01	3.84	1.47	2.06	3.96
T	90	65	80	90	75	65	70	65
S	395	148	191	90.9	288	95.6	144	257
W	1.61	1.51	1.50	1.42	1.57	1.44	1.38	1.08
I (smoke index)	245	98	127	64	183	66	104	238

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$
T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 32.—Smoke Index of Will County Briquets Volatilized to 16.4 Per Cent Volatile Matter at Temperature of 535°C. for 10 Minutes

Time (seconds)	Test samples			
	1	2	3	4
	Galvanometer deflections (mm.)			
0	222	225	224	229
5	217	223	221	224
10	217	220	216	224
15	217	220	209	225
20	219	221	204	224
25	217	215	209	223
30	214	216	210	224
35	211	218	215	223
40	210	214	216	221
45	211	218	218	223
50	209	222	221	223
55	222	221	223	223
60	210	224	....	222
65	210	....	....	224
70	215	....	....	226
75	220	....	....	226
80	221	....	....	226
85	....	....	....	225
90	....	....	....	224
95	....	....	....	220
100	....	....	....	223
105	....	....	....	226
Total	3662	2857	2586	4928
Number readings	17	13	12	22
A	215.4	219.8	215.5	224.0
B	221.5	224.5	223.5	227.5
X	2.75	2.09	3.58	1.54
T	80	60	55	105
S	220	125	197	162
W	1.38	1.30	1.41	0.86
I (smoke index)	159	96	140	188

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Franklin County briquets.—A similar series of tests was made for Franklin County coal. These smoke index results are shown in Tables 33, 34, 35, 36, and 37 for the products partially volatilized at temperatures of 250°, 450°, 465°, 480°, and 495°C., and containing 35.9, 33.1, 30.9, 28.5, and 23.6 per cent volatile matter, respectively. The same data are averaged and summarized in Table 7 (Part I of report).

In figure 6 (Part I of report) the smoke index is plotted against the volatile matter content for Franklin County coal in a manner similar to that in figure 5 (Part I of report) for Will County coal. This curve likewise indicates a linear relationship between volatile matter content and smoke index for Franklin County coal.

Table 33.—Smoke Index of Nonvolatilized Franklin County Briquets Containing 35.9 Per Cent Volatile Matter Heated at Temperature of 250°C. for 10 Minutes

Time (seconds)	Test samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (mm.)							
0	170	163	171	163	165	159	157	156
5	166	161	163	162	161	158	155	154
10	166	156	151	160	151	156	154	153
15	166	154	136	152	132	151	149	152
20	167	146	121	136	116	141	135	153
25	163	130	114	115	100	132	117	151
30	156	120	112	102	85	116	107	140
35	144	72	120	84	92	109	92	123
40	147	102	105	82	83	104	85	103
45	139	96	115	84	91	117	77	95
50	132	99	109	101	92	62	68	82
55	91	97	113	83	85	89	67	96
60	105	93	108	102	117	87	95	81
65	100	100	108	90	100	87	105	98
70	106	98	106	98	97	94	82	91
75	102	97	109	97	101	85	98	98
80	106	98	109	97	106	92	103	94
85	109	110	118	100	105	83	114	102
90	111	111	117	93	101	84	119	102
95	111	99	109	93	108	86	118	107
100	109	110	102	102	109	99	128	105
105	112	108	120	113	106	104	130	107
110	107	128	129	124	114	126	141	96
115	101	138	136	136	131	128	152	105
120	106	145	148	149	140	143	148	134
125	110	144	159	....	151	148	150	137
130	126	145	162	....	156	147	152	144
135	135	145	....	....	....	148	....	....
140	146	147	....	....	....	151	....	....
145	161	148	....	....	....	....	....	....
150	157	....	....	....	....	....	....	....
155	157	....	....	....	....	....	....	....
160	158	....	....	....	....	....	....	....
165	159	....	....	....	....	....	....	....
Total	4501	3660	3370	2818	3095	3386	3198	3159
Number readings	34	30	27	25	27	29	27	27
A	132.4	122.0	124.8	112.7	114.6	116.8	118.4	117.0
B	164.5	155.5	166.5	156.0	160.5	155.0	154.5	150.0
X	19.5	21.5	25.0	27.8	28.6	24.6	23.4	22.0
T	165	145	130	120	130	140	130	130
S	3218	3118	3250	3336	3718	3444	3042	2860
W	1.30	1.30	1.31	1.25	1.37	1.27	1.08	1.17
I (smoke index)	2480	2400	2480	2670	2710	2710	2820	2440

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) =

$$\frac{B - A}{B} \times 100$$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 34.—Smoke Index of Franklin County Briquets Volatilized to 33.1 Per Cent Volatile Matter at a Temperature of 450°C. for 10 Minutes

Time (seconds)	Test samples						
	1	2	3	4	5	6	7
	Galvanometer deflections (mm.)						
0	159	155	155	154	153	157	158
5	157	154	154	153	148	154	155
10	153	152	143	149	139	147	155
15	145	142	127	138	122	130	149
20	131	125	106	124	113	121	152
25	118	103	101	105	95	105	147
30	109	96	83	101	86	90	132
35	98	88	78	98	76	102	120
40	97	95	100	97	76	91	123
45	85	90	85	110	120	95	97
50	79	89	80	90	95	90	84
55	99	117	89	83	96	87	127
60	119	95	85	94	99	88	105
65	106	97	89	93	88	96	119
70	113	102	85	97	88	90	119
75	106	101	88	113	96	97	123
80	109	108	89	120	105	108	124
85	103	108	99	140	118	105	123
90	105	111	107	143	134	129	125
95	107	113	116	149	143	147	129
100	112	126	107	151	152	159	132
105	112	128	121	149	150	157	138
110	118	141	116	150	....	....	145
115	131	147	148	151	....	....	152
120	136	151	150	....	....	....	153
125	150	152	149	....	....	....	155
130	154	....	155	....	....	....	....
135	....	....	152	....	....	....	....
140	....	....	153	....	....	....	....
Total	3211	3086	3210	2952	2492	2545	3441
Number readings	27	26	29	24	22	22	26
A	118.9	118.7	110.7	123.0	113.3	115.7	132.3
B	156.5	153.5	154.0	152.5	151.5	157.0	156.5
X	24.0	22.7	28.1	19.3	25.2	26.3	15.5
T	130	125	140	115	105	105	125
S	3120	2838	3934	2220	2646	2762	1938
W	1.47	1.46	1.58	1.06	1.15	1.07	1.20
I (smoke index)	2120	1940	2490	2090	2300	2580	1620

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 35.—Smoke Index of Franklin County Briquets Volatilized to 30.9 Per Cent Volatile Matter at a Temperature of 465°C. for 10 Minutes

Time (seconds)	Test samples 1	2	3	4	5	6	7
	Galvanometer deflections (mm.)						
0	160	160	161	159	160	161	158
5	158	156	159	156	159	160	153
10	156	151	156	150	159	159	146
15	154	143	158	140	158	159	139
20	144	137	154	126	155	156	127
25	141	128	152	121	142	149	115
30	120	124	142	106	136	142	101
35	111	113	129	101	125	130	93
40	98	115	116	103	98	103	95
45	95	103	100	95	95	123	82
50	149	92	104	90	91	113	100
55	123	97	96	91	95	117	135
60	134	87	96	86	121	113	111
65	133	96	126	93	109	119	121
70	132	93	120	95	116	109	118
75	138	95	116	104	122	121	116
80	141	104	116	108	129	117	125
85	146	90	116	112	128	119	125
90	152	120	126	125	136	133	122
95	159	140	134	136	142	133	133
100	....	132	134	146	152	146	140
105	....	143	157	151	158	157	145
110	....	147	....	155	159	....	154
115	....	151	....	158	....	....	156
120	....	159	....	159	....	....	....
Total	2744	3076	2868	3066	3045	2939	3010
Number readings	20	25	22	25	23	22	24
A	137.2	123.0	130.4	122.6	132.4	133.6	125.4
B	159.5	159.5	159.0	159.0	159.5	159.0	157.0
X	14.0	22.9	18.0	22.9	17.0	16.0	20.1
T	95	120	105	120	110	105	115
S	1330	2748	1890	2748	1870	1680	2312
W	1.17	1.50	1.05	1.44	1.13	1.30	1.45
I (smoke index)	1140	1830	1800	1910	1650	1290	1590

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

Table 36.—Smoke Index of Franklin County Briquets Volatilized to 28.5 Per Cent Volatile Matter at a Temperature of 480°C. for 10 Minutes

Time (seconds)	Test samples 1	2	3	4	5	6	7
	Galvanometer deflections (mm.)						
0	156	157	165	162	163	162	160
5	153	154	164	161	161	161	157
10	154	155	164	159	159	159	158
15	156	154	161	154	160	152	154
20	154	152	155	146	161	140	146
25	153	155	147	139	157	126	137
30	149	152	147	140	150	113	126
35	143	149	126	121	137	110	119
40	136	144	134	127	129	103	115
45	129	137	124	122	124	99	115
50	126	129	122	119	125	113	105
55	127	126	121	116	135	109	107
60	117	119	125	110	127	110	124
65	122	115	140	115	133	119	123
70	111	107	128	112	131	128	116
75	116	111	141	118	131	123	125
80	140	98	144	118	134	129	128
85	149	108	151	122	138	138	130
90	140	113	160	132	142	140	133
95	147	106	163	140	144	152	140
100	151	110	....	151	144	161	147
105	153	113	....	157	149	158	151
110	157	120	....	158	153	....	156
115	....	128	....	159	158	....	....
120	....	137	....	160	160	....	....
125	....	148	....	....	....	....	....
130	....	156	....	....	....	....	....
135	....	154	....	....	....	....	....
Total	3239	3707	2882	3418	3605	2905	3072
Number readings	23	28	20	25	25	22	23
A	140.8	132.4	144.1	136.7	144.2	132.0	133.6
B	156.5	155.5	164.0	161.0	161.5	160.0	158.0
X	10.0	14.9	12.1	15.1	10.7	17.5	15.4
T	110	135	95	120	120	105	110
S	1100	2012	1150	1812	1284	1838	1694
W	1.15	1.27	1.23	1.38	1.37	1.14	1.39
I (smoke index)	956	1580	934	1310	937	1610	1220

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) $= \frac{B - A}{B} \times 100$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

TABLE 37.—SMOKE INDEX OF FRANKLIN COUNTY BRIQUETS VOLATILIZED TO 23.6 PER CENT VOLATILE MATTER AT A TEMPERATURE OF 495°C. FOR 10 MINUTES

Time (seconds)	Test samples							
	1	2	3	4	5	6	7	8
	Galvanometer deflections (mm.)							
0	160	160	161	161	160	159	169	168
5	159	156	159	159	157	157	165	167
10	157	156	156	155	158	158	166	166
15	156	157	159	154	158	157	168	165
20	155	157	159	148	158	156	166	163
25	156	157	156	147	160	154	166	156
30	155	152	157	145	159	149	164	155
35	153	156	153	143	159	146	162	150
40	153	158	153	138	160	143	159	145
45	155	158	155	141	159	142	159	141
50	153	159	155	145	159	142	168	137
55	153	160	155	144	158	138	161	146
60	152	161	154	144	161	138	158	147
65	154	...	157	...	...	144	161	141
70	156	...	156	157	...	139	165	146
75	158	...	155	159	...	142	168	167
80	158	...	159	161	...	138	...	161
85	160	...	161	...	...	148	...	165
90	...	...	...	...	...	147	...	168
95	...	...	...	...	...	162	...	...
100	...	...	...	...	...	159	...	...
Total	2803	2047	2820	2401	2066	3118	2625	2954
Number readings	18	13	18	16	13	21	16	19
A	155.7	157.5	156.7	150.1	158.9	148.5	164.1	155.5
B	160.0	160.5	161.0	161.0	160.5	159.0	168.5	168.0
X	2.69	1.87	2.67	6.77	1.00	6.60	2.61	7.44
T	85	60	85	80	60	100	75	90
S	228.7	112.2	227.0	541.6	60.0	660.0	195.8	669.6
W	1.31	1.30	1.29	1.31	1.29	1.47	1.15	1.40
I (smoke index)	175	86	176	414	47	449	170	479

A = average deflection.
B = average of initial and final deflections.
X = average smoke density (percentage) = $\frac{B - A}{B} \times 100$

T = total time (seconds).
S = total smoke = X × T.
W = wt. of sample (grams).
I = smoke index = S/W.

RELATIONSHIP BETWEEN SMOKE INDEX AND VOLATILE MATTER CONTENT OF BRIQUETS MADE BY IMPACT FROM PARTIALLY VOLATILIZED COALS

For both naturally occurring and artificially reduced volatile matter contents of the bituminous coals investigated, an approximate linear relationship exists between the smoke index and the volatile matter content. The slope

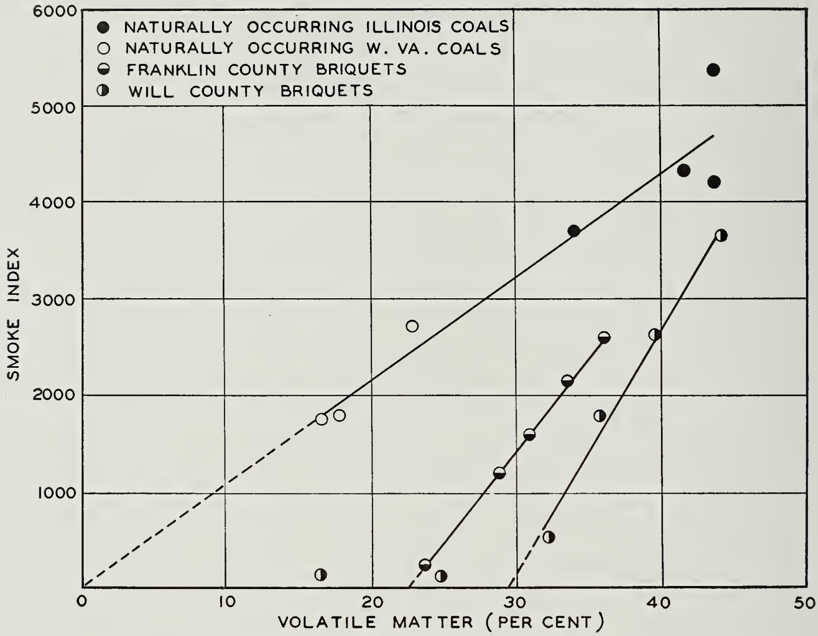

Fig. 16.—Effect of Amounts of Volatile Matter on the Smoke Index of Illinois and West Virginia Coals and Briquets Made From Franklin and Will County Coals. (Fig. 15, p. 90, and Figs. 5 and 6, Pt. I, pp. 27, 28.)

of the straight line for natural coals differs radically, however, from that of coal processed by the method herein described, as shown by figure 16 which is a composite of figure 15 and figures 5 and 6 (Part I of report).

RELATIONSHIP BETWEEN SMOKE INDEX AND VOLATILE MATTER CONTENT OF NATURAL BITUMINOUS COALS

Referring again to figure 15, which shows a straight-line relationship between smoke index and volatile matter content for the natural coals investigated, it may be noted that the dotted extrapolation line intersects the axes at their zero value. In other words, there is an approximate direct proportionality between smoke content and volatile matter content for these coals. This seems to indicate that (with respect to its smoke content) the type of

volatile matter present in these various coals is practically identical, the amount of the smoke per gram of the volatile matter being practically the same for the bituminous coals investigated.

However, it is well known that some coals possess a widely different smoke content from that of other coals containing the same percentage of volatile matter. It remains for future investigation to show whether or not a family of smoke index curves characterize coals having different botanical constitution.

SMOKE INDICES OF BRIQUETS MADE BY IMPACT FROM PROCESSED ILLINOIS COALS COMPARED WITH THOSE MADE DIRECTLY FROM NATURAL COALS

An examination of figure 16 shows a contrast in the rate of decrease of smoke index with volatile matter content for processed and natural coals. For example, in the instance of processed Will County coal (Fig. 5, Part I of report), the briquetted sample with a volatile matter content of 31.9 per cent (reduced from a natural volatile matter content of 43.9 per cent) has a smoke index of 250. Thus, processed coals from Will and Franklin counties can be made which possess less than one-third and one-seventh, respectively, of the smoke index of that of a natural West Virginia coal, even though the latter has a lower percentage of volatile matter.

IMPORTANCE OF ELIMINATING THE HIGH-SMOKE-INDEX FRACTION OF THE VOLATILE MATTER

Referring again to figures 5 and 6 (Part I of report), which show a straight-line relationship between smoke index and volatile matter content for briquets of partially volatilized coals from Will and Franklin counties, it may be noted that the dotted extrapolated lines intersect the volatile matter axis at 29 per cent and 23 per cent, respectively. Thus the smoke index decreases far more rapidly than the volatile matter content. This seems to indicate that in the process herein described there is a fractionation of the volatile matter whereby the high-smoke-index fraction is liberated, whereas the low-smoke-index fraction is retained in the processed coal.

Therefore for the purpose of obtaining a smokeless fuel for compaction into briquets from Illinois coals, it is essential only to apply heat sufficient to remove volatile matter which is driven off at comparatively low temperature.

RELATIONSHIP BETWEEN TEMPERATURE AND TIME IN EFFECTING DIFFERENT AMOUNTS OF VOLATILIZATION

This study consisted of: (a) the determination of the effect of volatilization temperature on the amount of volatile matter removed during a 10-minute volatilization period; and (b) the determination of time-temperature curve for 15 per cent volatile matter loss.

Effect of volatilization temperature on amount of volatile matter removed.—The effect of the temperature of volatilization on the amount of volatile matter reduction was determined for both Will and Franklin County coals using a volatilization period of 10 minutes.

Will County coal.—The effect of the temperature of volatilization, with a range from 350° to 530°C. (coal temperature), on the percentage of volatile matter in Will County coal, volatilized for a 10-minute period, is shown in figure 17 (Table 38). It may be noted from the figure that the volatile reduction starts at 420°C., the amount of reduction increasing with temperature.

TABLE 38.—VOLATILE MATTER CONTENT OF WILL COUNTY COAL AS AFFECTED BY VARIOUS VOLATILIZATION TEMPERATURES MAINTAINED FOR 10 MINUTE PERIODS (DATA FOR FIG. 17)

Volatilization coal temperature (°C.)	Oven temperature (°C.)	Weight loss (per cent)	Volatile matter (*a*) (per cent)
350	400	0.0	43.9
373	425	0.5	43.7
395	450	1.2	43.2
426	480	1.9	42.8
430	475	2.8	42.3
448	490	5.8	40.5
460	500	6.9	39.8
466	510	8.8	38.5
475	520	11.8	36.4
475	525	11.3	36.8
485	530	12.7	35.7
494	540	16.2	33.0
505	550	17.6	31.9
530	575	(*b*)	(*b*)

(*a*) Percentage volatile matter calculated from experimental weight loss.
(*b*) Weight loss could not be determined because no briquet was formed.

Franklin County coal.—Similar results for briquets made from Franklin County coal, volatilized for a 10-minute period at a coal temperature ranging from 250° to 482°C. are shown in figure 18 (Table 39). By extrapolation the initial temperature of volatile matter reduction appears to be about 410°C.

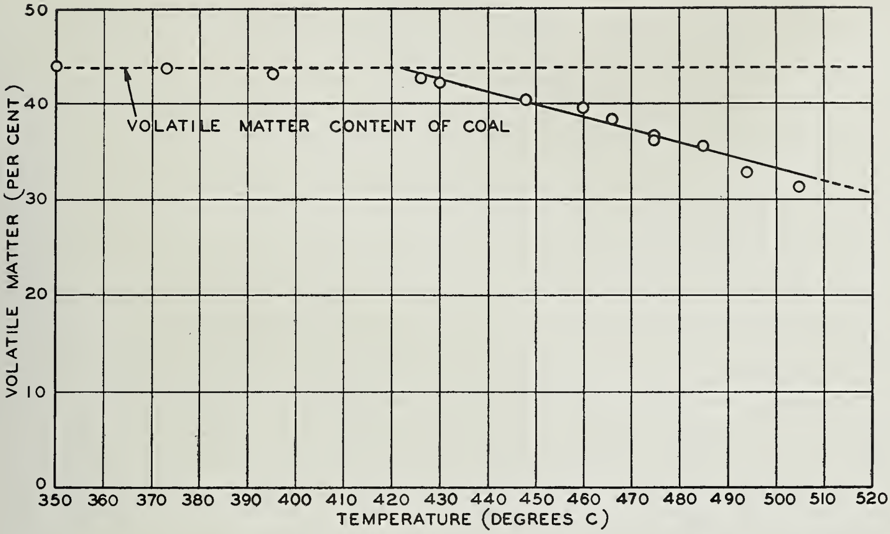

Fig. 17.—Volatile Matter Content of Will County Coal as Affected by Various Volatilization Temperatures Maintained For 10-Minute Periods.

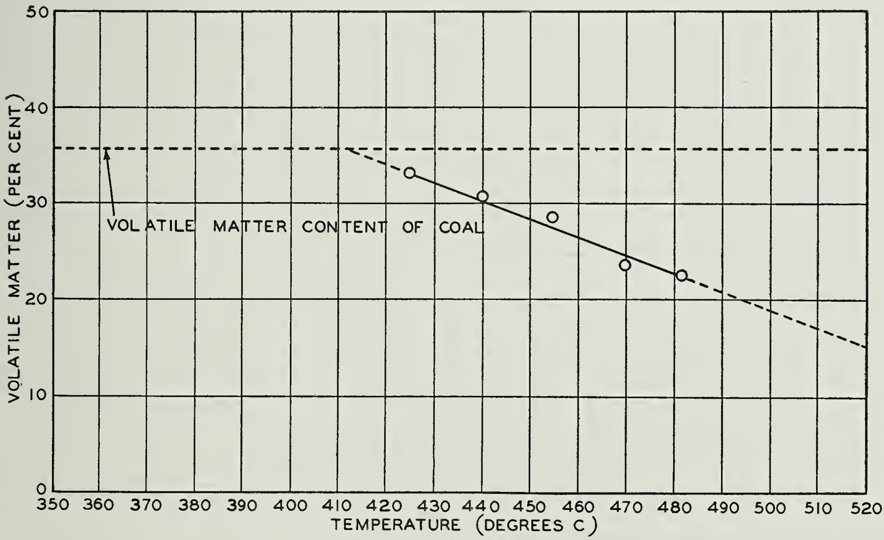

Fig. 18.—Volatile Matter Content of Franklin County Coal as Affected by Various Volatilization Temperatures Maintained For 10-Minute Periods.

Table 39.—Volatile Matter Content of Franklin County Coal as Affected by Various Volatilization Temperatures Maintained for 10 Minute Periods (Data for Fig. 18)

Volatilization coal temperature (°C.)	Oven temperature (°C.)	Weight loss (per cent)	Volatile matter (*a*) (per cent)
250	275	0.0	35.9
425	460	4.3	33.0
440	480	7.3	30.9
455	500	10.3	28.6
470	520	16.1	23.6
482	540	17.2	22.6

(*a*) Percentage volatile matter calculated from experimental weight loss.

TIME-TEMPERATURE CURVE FOR 15 PER CENT VOLATILE MATTER LOSS

Table 38 shows the volatile matter content of Will County coal volatilized at various temperatures for various periods of time. As shown previously (p. 28), on "as received" basis, a 15 per cent reduction in volatile matter results in a smokeless coal, with a smoke index less than one-third that of a West Virginia coal. For a coal containing about 10 per cent moisture, 15 per cent reduction on "as received" basis is equivalent to between 16 and 17 per cent reduction on a dry basis. Thus an optimum volatile matter loss of 16 per cent, dry basis, reduces this Will County coal from 43.9 to about 34 per cent volatile matter, which was selected as the optimum volatile matter content for smokeless briquets from this coal. Figure 4 (Part I of report) is a graph of the time-temperature curve for such an optimum volatile matter loss. As expected, the period necessary for the desired degree of volatilization decreases rapidly with increasing temperature.

DISCUSSION

For Will County coal, prevolatilized for a 10-minute period, volatilization starts at about 420°C., and the percentages of remaining volatile matter decrease linearly with temperature. For Franklin County Coal, volatilization starts at about 410°C., or 10° less than that for Will County coal. The percentages of remaining volatile matter, likewise, decrease linearly with temperature for the same period, the rate of decrease being apparently the same as that for Will County coal.

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